SPECIAL ISSUE

JANUARY 2021

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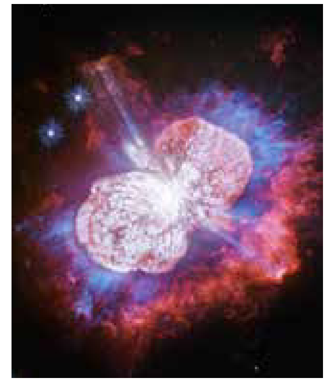

ON THE COVER

The strange, eruptive star Eta Carinae, as captured by Hubble, is one of the unusual treasures of the cosmos. NASA, ESA, N. SMITH (UNIVERSITY OF ARIZONA) AND J. MORSE (BOLDLYGO INSTITUTE)

FEATURES

IN EVERY ISSUE

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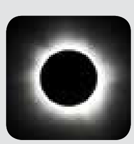

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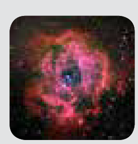

Picture of the Day
Gorgeous photos from our readers.

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FROM THE EDITOR

The beginning and the end

Massive galaxy clusters in the cosmos are the largest structures known, and hold secrets to the universe's fate.
ILLUSTRIS COLLABORATION

When my colleague Steve George suggested we do something really special with the January issue of *Astronomy*, I immediately thought of cosmology. What hadn't been done as a cosmic theme before?

Well, how about the entire chronological history of the universe, from start to finish? That was an ambitious target, but what you hold in your hands is the result, and I hope you will enjoy it very much.

In this issue, we explore summaries of what is known about the history of the universe, starting with the Big Bang through to the present, and also look forward all the way to the end of the cosmos. In between, we explore what fascinates us most about the universe: the fact that we're living beings within it. How did life arise on Earth? What are the odds for life, simple or complex, elsewhere, and how might we go about detecting it?

Of course, we've known that the cosmos began long ago since the Cosmic Microwave Background Radiation was discovered in 1964, and the Planck satellite has adjusted the date of origin to 13.8 billion years. The atoms in your body were created either in Big Bang nucleosynthesis early in the universe's history or in the deaths of massive stars since. And high confidence exists in the concept of cosmic inflation, dreamed up in the 1970s, which means the visible universe we see is not the whole shebang.

As for what will happen in the distant future, we don't know for sure, with wild cards like dark energy in the equation. But it seems the universe may have a cold, lonely, dark ending — a whimper. Don't let that get you down as you read about the most fascinating story there is, the tale of everything that ever was, or ever will be.

I hope this information-rich package will offer lots to think about in this unusual time of isolation, and also allow you to squirrel away plenty of interesting facts and questions for cocktail parties of the future.

Yours truly,

David J. Eicher
Editor

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True physical properties of Light

(Rays of all kinds); A New Discovery claim.

Light does not have dual properties of wave and a particle. It has only one property that a ray of light consists of closely touching materialistic spherical particles.

If Discoverer Ramesh Varma (India) had been academic qualified PhD scientist (not citizen scientist); discovery claim instead of being an advertisement, would have appeared in all Science Journals as publication resulting to make it viral among the concerned. (Mode of new discovery information set by the Academic World is a curse on the mankind).

Ibn al-Haytham, known Scientist of the past made significant advances 1000 years ago in optics (light), mathematics and astronomy. He is known to have said "If learning the truth is the Scientist's goal... then he must make himself the enemy of all that he reads". By this he meant it was essential to conduct experiments to test what is written rather than blindly accepting it as true.

Correct understanding of true physical properties of 'Light' is the key to correctly understand formation and working mechanism of the solar system thus of the Universe and every thing/life within it.

To date, the World has not been able to understand Light correctly. History of Light reveals that some concerned have concluded that Light is a wave and some observed Light is the stream of particles. Finally, Physicists to close the door for any further debate over properties of the Light have come with the idea to declare that Light has dual properties of a wave and a particle. They fit property (wave or particle) of Light, where it fits to proceed ahead and left the Astronomers in lurch from correctly understanding basics of the Astronomy. Basic Astronomy and working mechanism of the solar system based over materialistic particles rays should be the subject of Physicists. Otherwise, human would go extinct without correctly understanding light and astronomy.

So far both the subjects Light and Astronomy float over theories, postulations, hypothesises and speculations; none of it stands for the fact.

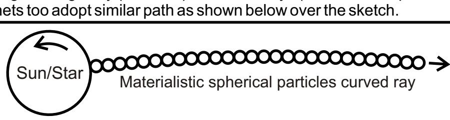
Light is the finest and lightest form of matter and particles move fastest. Due to the said fact Human cannot develop any scientific device or can build a scientific laboratory of any kind and anywhere (over the Earth, underground or in space); where correct physical properties of the Light could be known or verified. To know **true physical properties of the Light**; one has to observe/visualize/understand like Discovery Claimer by considering Solar Space as Nature's vast Laboratory and whatsoever is in the Solar Space (like Sun, planets, satellites, asteroids, comets, dust etc) that should be considered as the scientific devices. By knowing how the rays of the Sun affect the existence and working of each solar body; **true physical properties of the Light** can be known (or verified)

Conclusion by the Discovery Claimer:

Light is not merely a form of energy; it is a state of the matter which acts as energy under specific conditions. Light is not like a living body (human) that can adopt double standard. In fact light has only one property that it is materialistic (a state of the matter) and it is composed of finest form of spherical particles. All particles propagate while closely touching each other as shown below over the sketch.

Row or ray of light composed of finest form of spherical particles.

Such kind of particles ray adopts a curved/ spiral path on its propagation while emerging from a spinning/rotating body (like, Sun). Radiation rays (materialistic spherical particles rays) from the planets too adopt similar path as shown below over the sketch.



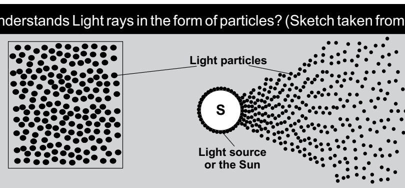
As the ray advances from its source, it keeps on shedding its overlapping to occupy the space ahead by diluting its intensity and density too. Further, materialistic spherical particle rays obey all laws of light, like reflection, refraction, diffraction etc.

Comparison of understanding Light as stream of particles understood by the World and ray of materialistic spherical particle rays by the Discovery Claimer:

It surprises the Discovery Claimer that so far no one has come with the correct explanation of particle behaviour of Light (though scientists have virtually accepted that Light has dual property of wave and a particle). Exhibited below are some sketches taken from the Internet showing how the scientists understand Light in the form of particles which makes no sense to the understood theory of particle property. Particle ray understood by the Scientists does not coincide with wave of light to even falsely accept dual property of the light as wave and particles. In fact Physicists have done so intentionally to up keep wave theory because they all have read and accepted it and done PhD and higher education level while accepting a ray as a wave. Now due to vested interest and mind set their mind does not accept any other version other than the wave theory.

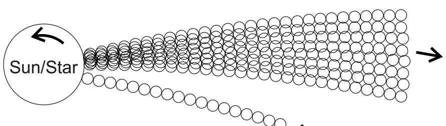
1. Propagation of light rays:

What the World understands Light rays in the form of particles? (Sketch taken from Internet).



From Magazine 'Astronomy' issue October 2014, Page 29

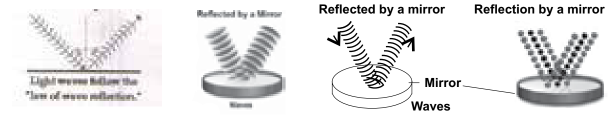
What the Discoverer has understood Light ray formed of materialistic spherical particle?



Materialistic spherical particles curved rays

2. Reflection of light rays:

Reflection of the ray in the form of particles and waves understood by the World. (Sketch taken from Internet).



(One of the wave mode) (One of the wave mode) (One of the wave mode) Particles Light ray

What the Discoverer has understood reflection of light in the form of materialistic spherical particles ray.

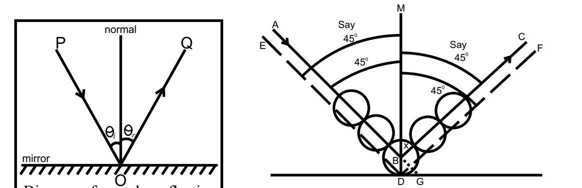
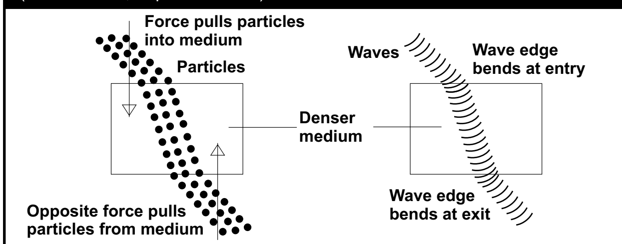


Diagram of specular reflection Reflection by the ray of microest-spheres

In the above sketch particles (spheres) of the light rays have been shown of big size to understand but in fact a ray of light is composed of microest-spheres, so thin/fine are the particles that we have no means to draw such a fine row of spheres which would seem to be a line as shown above.

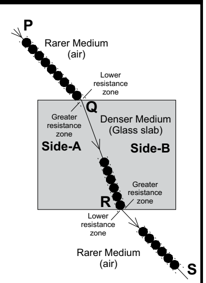
3. Refraction of light rays:

Refraction of the ray in the form of particles and waves understood by the World: (From Internet, September 2009).



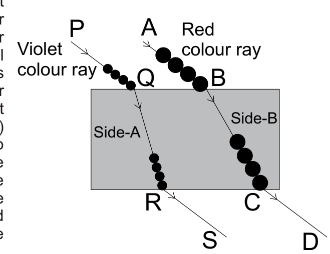
Refraction by the particles-rays as understood by the Challenger.

When a monochromatic particle ray PQ from rarer medium touches the denser medium at point Q; the microest sphere at interface which touches the denser medium faces difference in resistance over its hemispheres towards side (Side-A) than the opposite side to it (Side-B). This difference in the resistance to particle on its entry to denser medium (greater resistance to hemisphere of the particle towards Side-A) results to spin the particle a little resulting to bend the materialistic microest sphere (particle), thus the ray bends in direction QR towards Side-A.



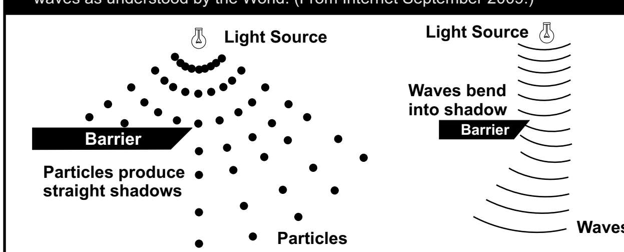
Microest-sphere (materialistic-particle) in the rays QR when touches at R; it again faces the difference in resistance to its either side hemispheres but in the opposite magnitude than the resistance faced at Q. Thus the ray particle at R again spins a little resulting to bend the ray QR but in the opposite direction.

Different coloured-rays of light: Rays of different colours of light have different wave-lengths or different sizes of their particles besides difference in their densities. By ignoring different densities, all the rays of light which have different colours would deviate differently because of their different sizes (surface area) and different total mass. Small particles (violet-rays) would deviate to greater angle due to greater resistance difference between the hemispheres of the particles towards the side-A and side-B than the resistance difference over hemispheres to large sized particles of the Red-ray because of the factor surface area and mass ratio. Explanation of said factor is ahead).



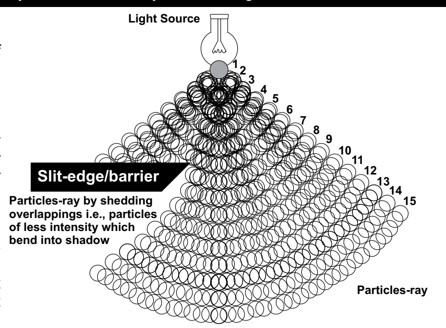
4. Diffraction of light rays:

Diffraction of the rays at the edge barrier (or through a narrow slit) as particles and waves as understood by the World. (From Internet September 2009.)



Paid advertisement of a new discovery claim pertaining to true physical properties of Light.

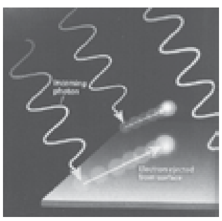
Diffraction of particles rays as understood by the Challenger.



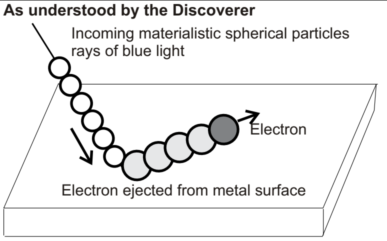
Light/ray consists of microest spheres and on moving at high speed just over the edge creates perfect-vacuum (white matter vacuum but not air vacuum) like water or air would create vacuum while flowing at high speed. Because of the vacuum of white-matter created by the particles of the ray at step No.7, the next particles of the ray at step No. 8 of the light/ray consisting of microest spheres would shed overlapping to fill the white-matter vacuum space over the edge and so on thus light forms diffraction over the edge and bends into the shadow. Further, because speed of the particles is very high, so light/ray would bend a little (not too much as shown over the sketch because of large sized particles) into the shadow to follow flared path.

5. Photoelectric effect confirmed that light is a stream of particles.

From ASTRONOMY magazine July2009.



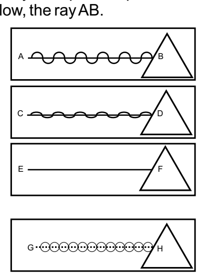
As understood by the Discoverer



Why do calculations done over the laws of light by understanding it as a wave and by considering a ray consisting of closely touching materialistic spherical particles are the same?

Truly speaking a ray of light does not propagate in the form of wave. Some following sketches would make the concerned understand that why both show the same result.

When a concerned has to study or to calculate the path of a ray in wave motion while it has to pass through a prism or glass slab etc, the concerned always adopts one phase i.e., plane parallel to the paper or to the computer screen as stated below, the ray AB.

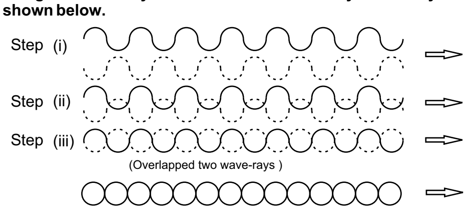


- This phase of the wave-ray AB always lies in the plane of the paper or screen of the computer.
- The same ray (CD) in wave motion at 450 to the plane of paper/computer-screen: This understanding of the rays would results to lower its amplitude thus the calculated results.
- If we have to draw this wavy ray (ray travelling in wave motion) perpendicular to the paper, it would be seen a straight line EF.
- Now if we rotate the wave AB to its axis AB. This could form an unlimited numbers of versions at every degree of rotation. Now if we spin fast this wave to its axis AB, it would form a chain of spheres. This chain of spheres would follow all the laws of light, which concerned falsely attempt to understand that a ray of light travels in wave motion.

- **<u>Conclusion from above sketches:</u>** By sketching a ray at different planes as shown above (in wave form) every Concerned calculates the result (travelled path after reflection/refraction etc) of a ray by understanding the ray as a wave but actually by camouflaging a wave-ray to spherical-particle-ray as shown over the sketch.

Overlapping of two wave-rays: Overlapping of two waves of the same specifications would result to form a ray similar to ray composed of closely touching spherical particles.

Bring two wave-rays closer and closer till they form a ray of spherical particles as shown below.



Note: Overlapped two wave rays is a ray similar to ray composed of closely touching materialistic spherical particles rays.

CONCLUSION:

1. Lightning (electrons) adopts the shortest path then why a ray of light would adopt the longer path to travel in waves?
2. No two different versions of the laws can yield the same results in science but these two stated understandings give result so, strange but true. **Why so? This all is due to the said error (blunder error of understanding).**
3. From more than a century World adopted the mode of understanding that light has dual property of wave and a particle. Why does the World not yet come with the finding that when light of a particular wavelength behaves as particle then what is the diameter of the particle?

Discovery Claimer has no laboratory or any devices with him to verify it. So, it is with the Physicists to find it. Discovery Claimer has concluded from the understanding of the World about the wave of light that if frequency is taken into account then diameter of the light particle would be equivalent to its wavelength and if amplitude and wavelength is taken into account then diameter of the particle would be half of the wavelength.

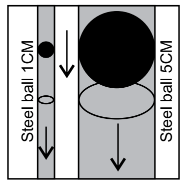
Speed of different colour rays:

World knows that in vacuum all colour waves travel at the same speed called 'c'; light of different wave lengths or colours, travels at different speeds when they travel through any medium other than vacuum, violet travels the slowest and red travels the fastest. Reason behind it, the World understands that red colour has longer wave length than the violet thus red travels at faster speed than the violet.

In fact it is not so. Light of red colour has bigger spherical particles than the violet colour. Violet spherical particles being of smaller diameter than the red thus they face greater resistance while passing through the medium due to their surface area-mass ratio. Below are some examples which confirm that smaller spherical matter faces greater resistance than the bigger during passing through the medium.

Examples: If two steel balls of 1cm and 5cm are dropped from a height at the same time; steel ball of diameter 1cm would fall with slower speed than the 5cm ball due to higher resistance faced with the air because of mass-surface area ratio. In vacuum (no air zone) column both balls would fall with the same speed. (Perfectly it is not possible because of white matter, which exists in vacuum column). Another example is also here; If two air bubbles (spheres) are released at the same time from the bottom of a vertical long glass jar filled with water. Smaller air bubble (sphere) would move upwards with slower speed than the bigger bubble due to the same factor as stated above.

Practical:



Cross section of the air column from which 1cm diameter and 5cm diameter ball has to fall due to gravity pull is 0.786cm^2 and 19.64cm^2 whereas their weight is 4.106gms and 513gms respectively. To disperse 1cm^2 of air column's cross section, mass of the smaller ball is equivalent to 4.106÷0.786= 5.22gms and whereas to disperse 1cm^2 of air column's cross section, mass of the bigger ball is equivalent to 513÷19.64 =26gms. **<u>Conclusion:</u>** To disperse 1cm^2 of air column smaller ball would exert a force due to gravity of 5.22g whereas the bigger ball would exert a force of 26g thus smaller ball would fall slowly than the bigger ball.

Speed of light in vacuum too is not the same for all colours because the difference in speeds is so minor that it is not possible to detect unless some sophisticated devices are developed. Vacuum (no air zone) is not absolute nothing zone but it is occupied by the white matter (falsely understood by the World as dark matter). White matter zone too poses resistance to light; had space been absolute nothing; light would not have a limited speed but speed would have been infinite; truly speaking then light would not have existed.

What about Einstein's equation e=mc^2?

In the equation 'e' is for the energy, 'm' is for the mass and 'c' suggests that initially when Einstein conceived the equation in his mind; he must be searching for a suitable constant that is why he put 'c' in the equation. Later he would have conceived the idea to put velocity of light in metres (3,00,000 kms/sec) in place of constant. (If length of a metre was equivalent to 30 inches or 50 inches than the existing length; speed of light would not have the same numerical then what would be the status of the equation? Imagine it. At that time influence of Einstein was so great that concerned would have accepted the equation as correct even if a metre had length 30" or 50" or any other than the existing; it might be possible that equation would have existed till date as correct). World must put constant (may be the speed of light i.e., 3,00,000 Km/Sec) for 'c' but without linking it to the speed of light; it would do away with most of the wrong understandings to correctly know the light and the Universe. Speed of light from core of the Sun to its surface is not the same as it is in the solar space. Due to thinning of white matter presence in the space at far away from the planetary zone; speed of light might be more than that understood. So, relationship of energy with the speed of light might not be proper.

Further, Due to linking of 'c' to velocity of light; Physicists have falsely understood that light particles (photons) have no mass and Physicists also claims that high gravity pull of Black hole bends the light rays. (When photons have no mass then how the light rays bend due to gravity pull?)

Most phenomena related to Astronomy prove that light is a ray composed of closely touching materialistic particles curved rays and light (rays of any kind) is not a wave.

Physicists and Astronomers have accepted that light ray consists of particles. How particles of the light ray propagate; they have not yet understood correctly? Rays of light (or any kind of rays) consisting of closely touching particles act to perform the following phenomena.

Acceptance of materialistic spherical particles curved rays concept has resulted to prove that:

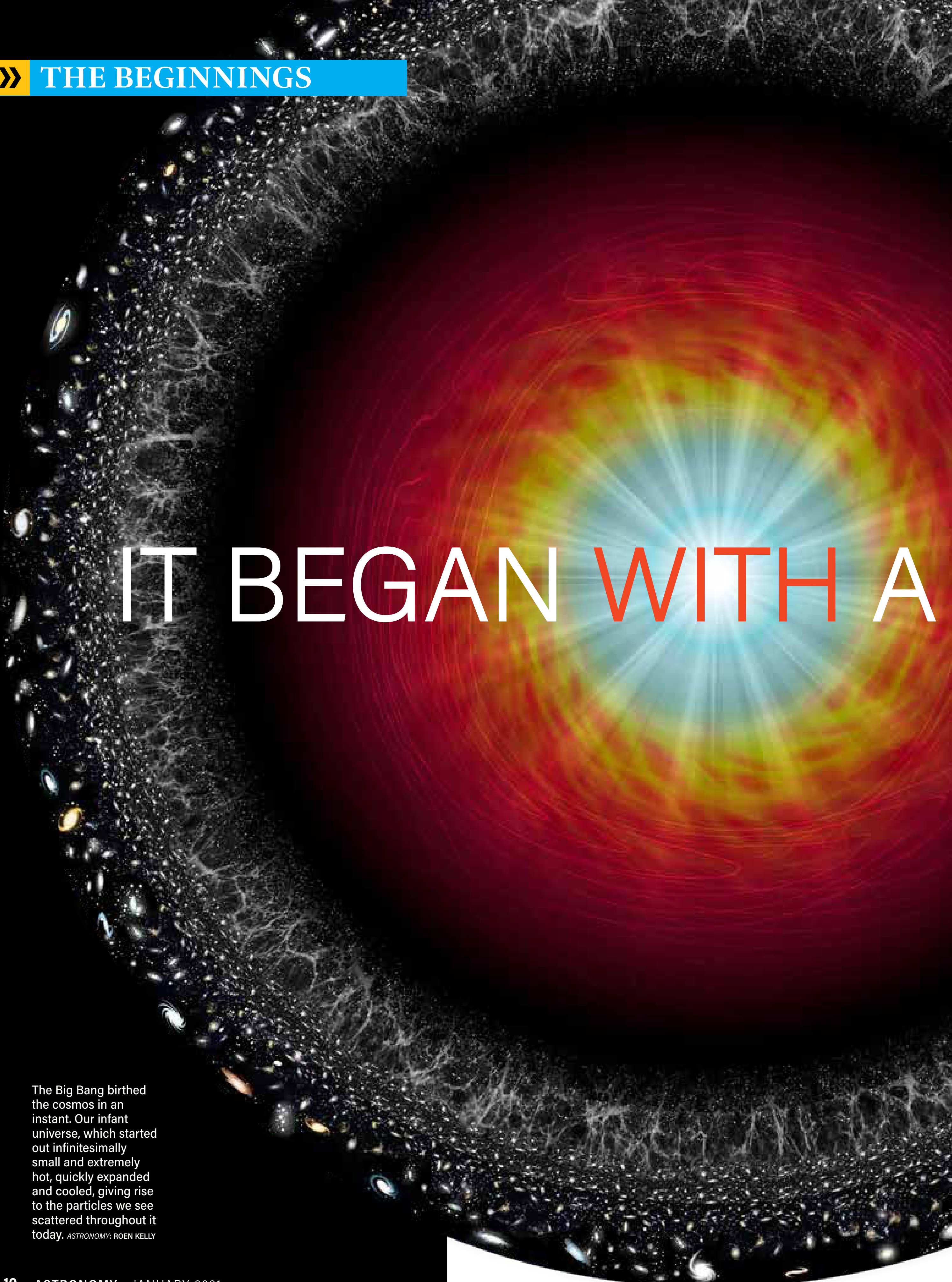
- How and why planets rotate?
- How and why some planets rotate faster and some slower?
- How and why some planets like Venus rotate in the reverse direction?
- How and why axis of the planets got tilt?
- How and why planets orbit around the Sun?
- How planets got their flat rings?
- How and why Jupiter has formed Trojans?
- How and why hexagonal swirling cloud tower at the planet Saturn's Pole formed?
- How and why the Sun keeps its family almost over a plane passing through its equator?
- How and why the Sun rotates with different speeds; faster at its equator than near to its Poles?
- How and why the Sun is a perfect sphere though it rotates faster?
- How and why the Universe is expanding outwards?
- How and why the galaxies rotate?
- How and why a comet does not orbit in elliptical orbit but adopts a loop track path?
- And much more beyond explanation over here.

(Whatsoever may be the reason(s) behind above said phenomena but what the World understands to date that all is wrong/false and rubbish)

Note:

- Understanding of the light consisting of closely touching materialistic spherical particles is primarily to understand true working mechanism of solar system along with the factor gravity. True knowledge over the solar system is the key to understand the Universe and every object and space within it.
- It is now up to the Physicists to know about light better than stated above by the Discovery Claimer.
- Physicists must read previous seven advertised discovery claims in the magazine 'ASTRONOMY' which appeared from February 2020 to August 2020 to know better that what is light.
- And must see on YouTube new discovery: Rotation to Sun by its materialistic particles rays.
- Read in detail the discovery claim MATERIALISTIC UNIVERSE on website: www.newtonugeam.com
- Please reply that why above stated discovered and claimed facts are not correct. E-mail: ramesh_varma@newtonugeam.com

IT BEGAN WITH A



The Big Bang birthed the cosmos in an instant. Our infant universe, which started out infinitesimally small and extremely hot, quickly expanded and cooled, giving rise to the particles we see scattered throughout it today. *ASTRONOMY*: ROEN KELLY

Our universe's earliest moments are the hardest to explore. But they hold the key to understanding the cosmos. BY DAN HOOPER

Over the course of the past century, astronomers and physicists have produced an incredibly rich and detailed account of our universe's history. In 13.8 billion years, our universe has expanded and transformed from the hot and dense state that we call the Big Bang into the vast cosmos that we find ourselves living in today.

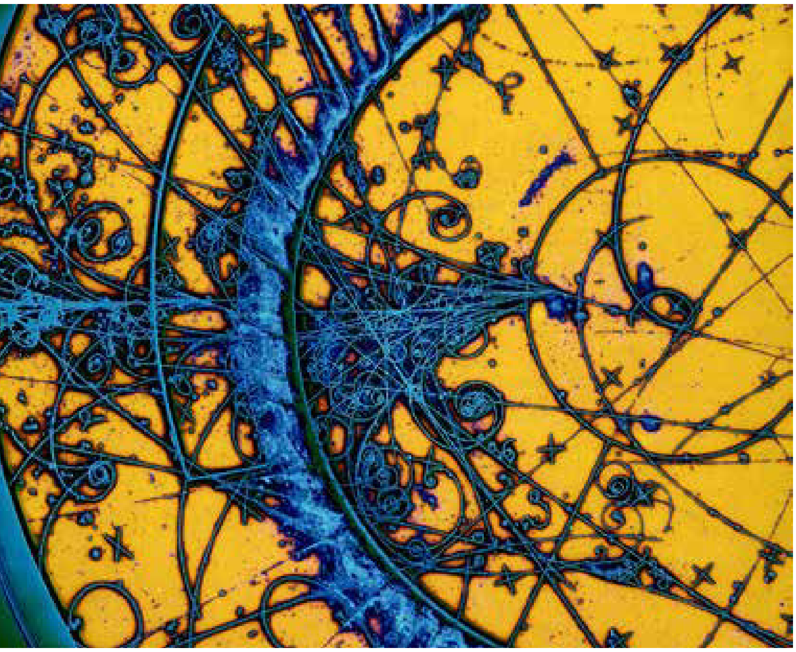
This picture is not based on mere speculation or theorizing, but is solidly grounded in an enormous body of empirical evidence. We have directly measured how our universe has expanded and evolved over the past several billion years, as well as how galaxies and clusters of galaxies formed. Looking back even further in time, we have scrutinized the light that was released during the formation of the first atoms, only 380,000 years after the Big Bang. We have even measured the abundances of deuterium, helium, and lithium that were forged through nuclear fusion in our universe's first seconds. Through these and other observations, we have become the first generations to understand our universe's distant past.

Reaching back

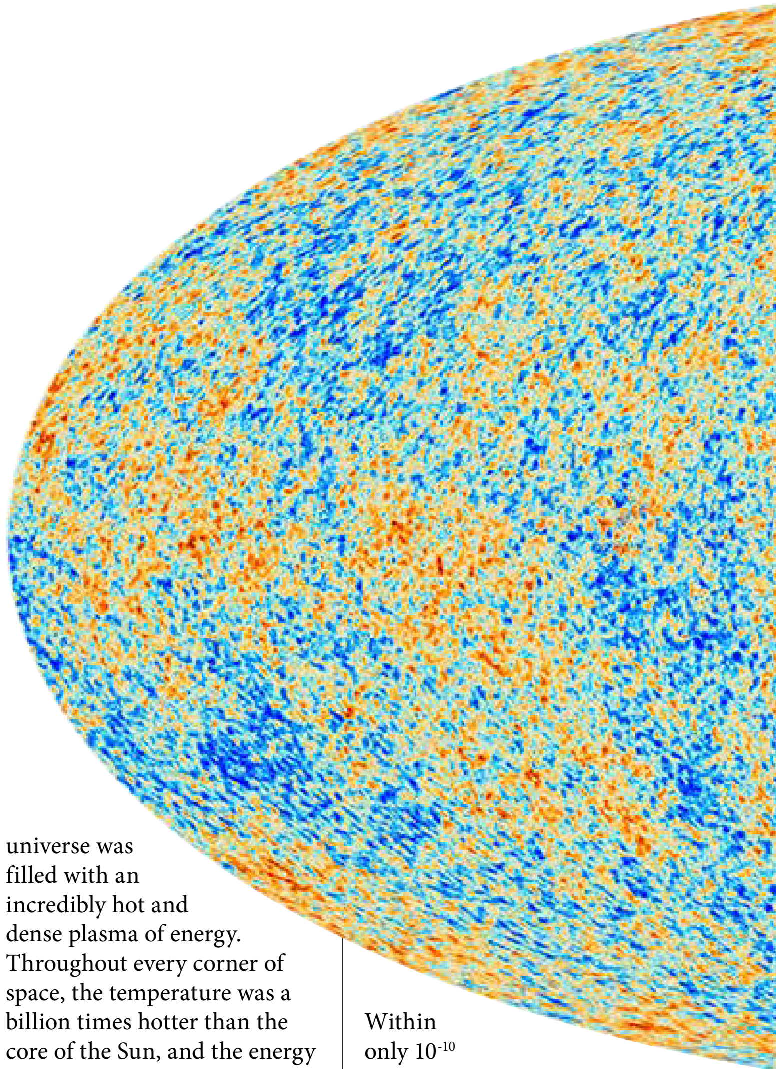
But when we attempt to reach back even further in time, earlier than those first few seconds, we find ourselves with almost no direct observations to test our theories. To our considerable frustration, this most intriguing of all eras remains hidden from our view, buried beneath as-yet impenetrable layers of energy, distance, and time.

However, that has not prevented physicists from learning about this formative era of cosmic history. Rather than relying on telescopes, we use particle accelerators to re-create the conditions that were found throughout our universe during the first fraction of a second after the Big Bang. These spectacular machines accelerate beams of particles — typically protons or electrons — to the highest speeds possible and then collide them into one

The Large Hadron Collider near Geneva, Switzerland, whose circumference is nearly 17 miles (27 km), allows physicists to re-create the conditions of the early universe. By smashing particles together at high speeds, researchers can study the interaction of matter and energy in conditions that don't exist today. CERN



Although subatomic particles are too small to see, certain detectors make visible the tracks left behind when they collide and interact. These so-called event displays are both beautiful and informative, allowing researchers to trace back the interactions of particles, like observing the skid marks left behind by an automobile collision. CERN



another. Through the power of Einstein's most famous equation, $E = mc^2$, the kinetic energy of motion in these collisions can transform into matter.

The Large Hadron Collider (LHC), for example, is capable of creating all of the known particle species, from electrons and photons to Higgs bosons and top quarks. The early universe was filled with these kinds of particles, all constantly interacting with each other, being repeatedly created and destroyed. By using the LHC to re-create and study these conditions, we have started to piece together the story of our universe's earliest instants.

A universe in flux

A trillionth of a second after the Big Bang, our entire universe was filled with an incredibly hot and dense plasma of energy. Throughout every corner of space, the temperature was a billion times hotter than the core of the Sun, and the energy density was equivalent to more than 10^{35} pounds in every cubic foot (10^{36} kilograms per cubic meter). Under these ultra-hot and ultra-dense conditions, every particle was constantly smashing into others. Within even a fraction of a trillionth of a second, the energy possessed by a given particle would change forms many trillions of times. Energy in the form of an electron might be converted into a photon, then into a Higgs boson, followed by the creation of a top quark, transforming over and over again. Nothing was permanent in this era. Everything was in flux.

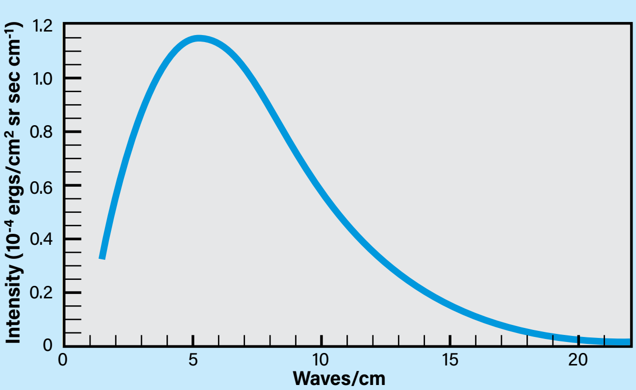
During these first moments, space was expanding at a staggering rate. Between 10^{-12} and 10^{-9} second after the Big Bang, the volume of our universe increased by a factor of about 30,000, and the temperature dropped by a factor of 30.

Within only 10^{-10} second, the temperature had dropped far enough that top quarks — the most massive of the known particles — began to disappear more often than they were being created. In a fraction of a blink of an eye, top quarks, Higgs bosons, Z bosons, and W bosons had each vanished almost entirely from our universe.

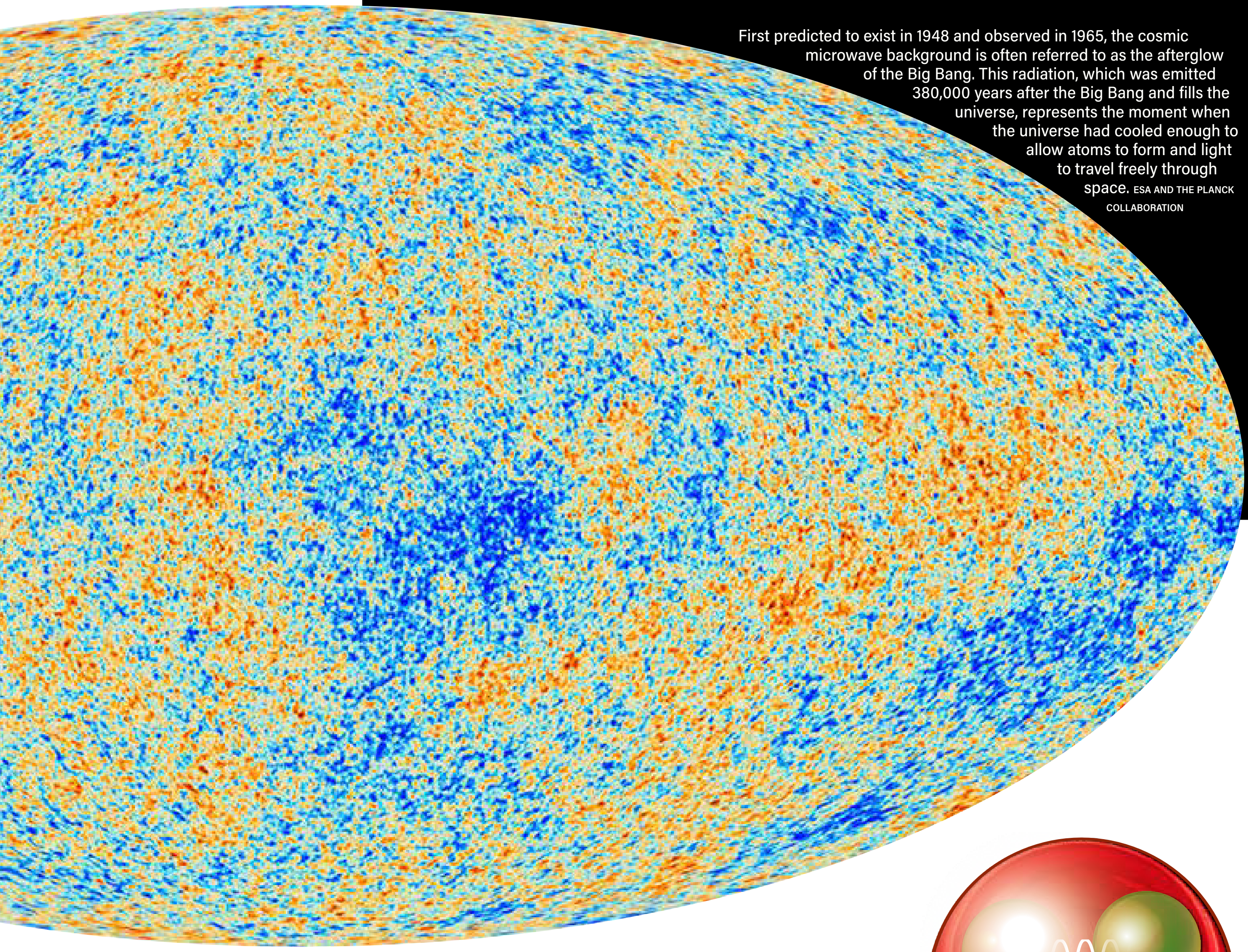
As time went on, the composition of the particles found throughout our universe continued to evolve. This began with the disappearance of the heaviest forms of matter, but other changes soon followed.

For example, up to this point in time, quarks and gluons, the subatomic particles that bind quarks together in atomic nuclei, had both been free particles. That is, a given quark or gluon would move through space on its own, interacting with other forms of matter

THE BIG BANG'S LIGHT



In 1990, the Cosmic Background Explorer satellite observed the spectrum of the cosmic microwave background in frequency versus intensity to measure its temperature. The results, based on 43 measurements at equal spacing along the curve, match the temperature predicted by the Big Bang theory so exactly that the uncertainties are smaller than the width of the blue line used to draw the curve. *ASTRONOMY*: ROEN KELLY, AFTER FIXSEN ET AL. 1996



First predicted to exist in 1948 and observed in 1965, the cosmic microwave background is often referred to as the afterglow of the Big Bang. This radiation, which was emitted 380,000 years after the Big Bang and fills the universe, represents the moment when the universe had cooled enough to allow atoms to form and light to travel freely through space. ESA AND THE PLANCK COLLABORATION

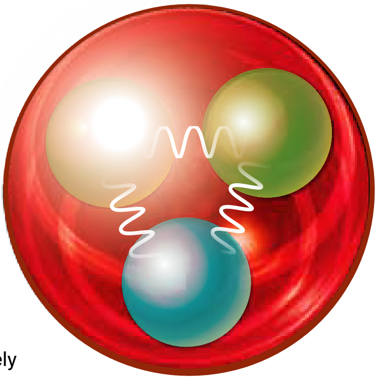
and energy just as any other particle might. But around 10 millionths of a second or so after the Big Bang, these particles began to find themselves irresistibly attracted to one another. Within a fraction of a millisecond, all of the quarks and gluons had become bound together into small groups, forming composite objects such as protons and neutrons — the building blocks of elements to come.

Seeking answers

There is no question that we are living in a golden age of cosmology. We know far more today about our universe and its history than we could have imagined only a few decades ago. But despite these successes, there are many perplexing questions that remain unanswered.

For one thing, in order to explain the simple fact that atoms exist in our universe, we know that there must have been slightly more matter than antimatter early on — or else all matter would have been annihilated by its antimatter equivalent. But the cause of this imbalance remains a mystery.

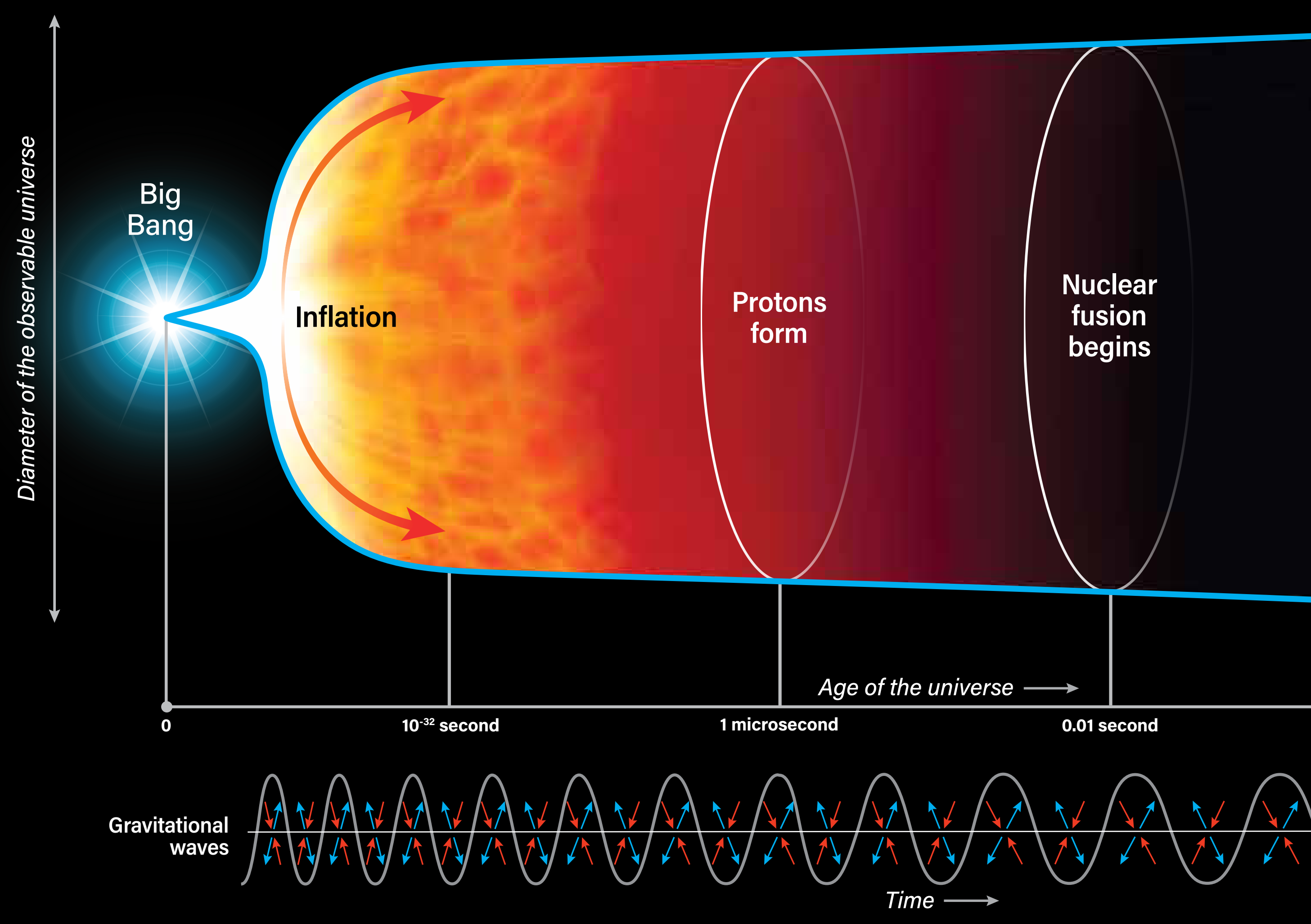
We also know that dark matter — the unknown substance that makes up the majority of the universe's matter — was formed at some point in the first second after the Big Bang, but we don't know how or when. Perhaps most striking of all, in order to explain the observed shape and uniformity of our universe, cosmologists have been forced to conclude that space must have undergone a brief period of hyperfast expansion during its very earliest moments. (See "Inflating the universe," page 14.) This era of cosmic inflation left our universe utterly transformed, and yet we know very little about it.



Today, the particles that make up normal matter — known as baryons — consist of quarks (smaller particles) bound together by gluons (white). Immediately after the Big Bang, however, the universe was so hot that quarks and gluons moved freely without sticking together. *ASTRONOMY*: ROEN KELLY

Mysteries such as these continue to drive the field of cosmology forward. New telescopes and experiments, as well as creative new ideas, will undoubtedly reveal to us new facets of our universe and its early history, as well as the path it took from there to here.

Dan Hooper *is a senior scientist at the Fermi National Accelerator Laboratory and a professor of astronomy and astrophysics at the University of Chicago. He is the author of* At the Edge of Time: Exploring the Mysteries of Our Universe's First Seconds *(Princeton University Press, 2019), and a co-host of the podcast* Why This Universe?



INFLATING THE

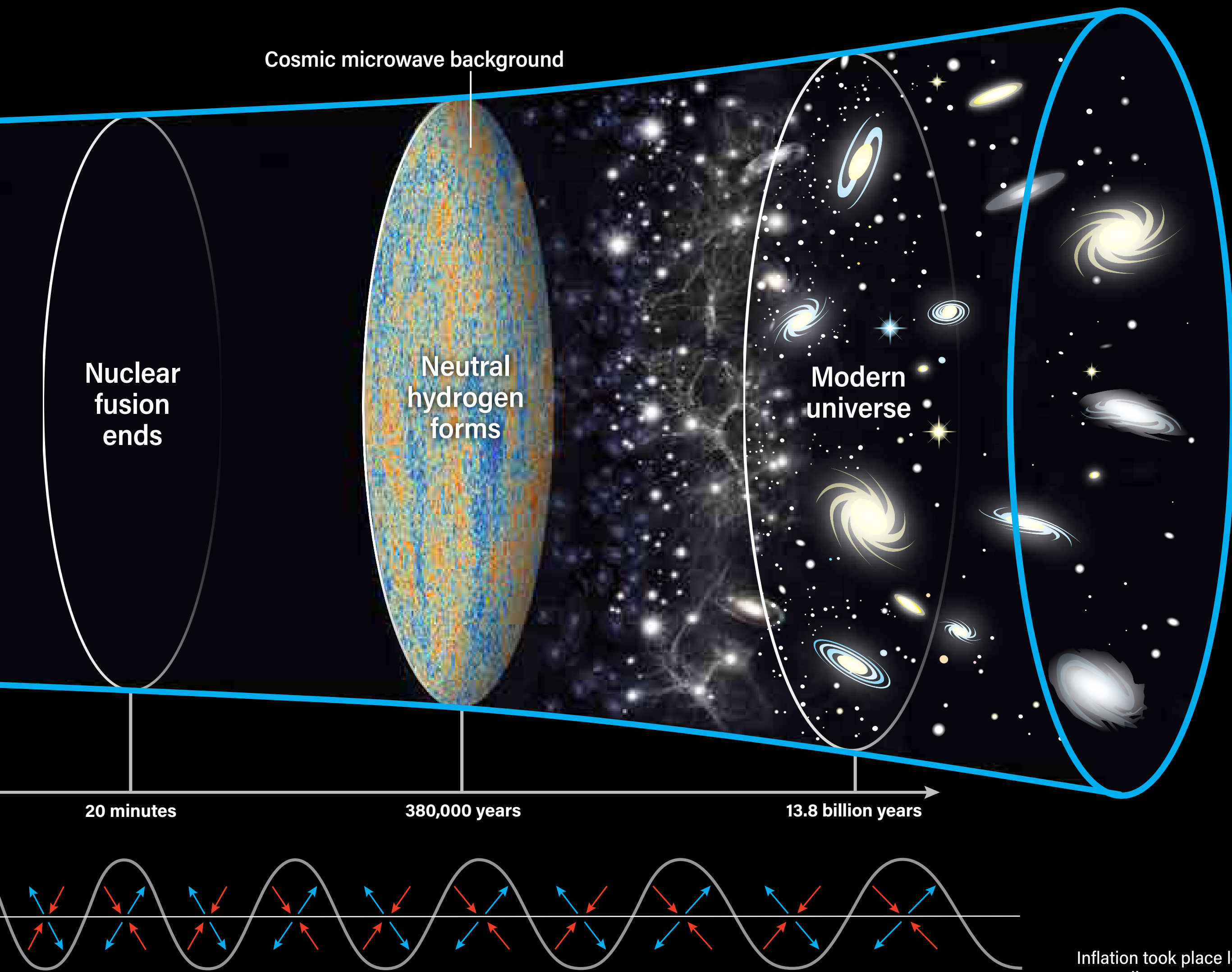
In a trillionth of a trillionth of a trillionth of a second, our universe underwent a growth spurt

Cosmologists are confident the Big Bang accurately describes the universe we see today. But they are less sure of what came before.

Stephen Hawking considered this inquiry pointless, like asking "What's south of the South Pole?" While often conflated, the Big Bang and the origin of time are distinct epochs. But what happened before the Big Bang may have laid the foundations for what came after.

The Big Bang theory describes the era starting when the lightest elements were formed — called Big Bang nucleosynthesis (BBN; see "The emergence of matter," page 18) — until today, where distant objects are receding at great velocities. BBN is currently the *last* epoch of certainty, the final stage in reverse cosmic history where the underlying forces of nature were similar to physics accessible to modern-day particle accelerators.

Beyond BBN lies speculation. The most popular model for what preceded it is *inflation*. Alan Guth, who began developing the theory in 1979, wrote in his book



Inflation took place long before our earliest snapshot of the universe, the cosmic microwave background (CMB). This dramatic process magnified local density fluctuations and equalized the universe's temperature to create the smooth CMB we observe. Inflation is believed to have generated gravitational waves, which should have left their mark on the light of the CMB. *ASTRONOMY:* ROEN KELLY, AFTER BICEP2 COLLABORATION

UNIVERSE

that shaped the structure we see today. **BY BRIAN KEATING**

The Inflationary Universe that "the standard Big Bang theory says nothing about what banged, why it banged, or what happened before it banged. The inflationary universe is a theory of the 'bang' of the Big Bang."

Ironing out the details

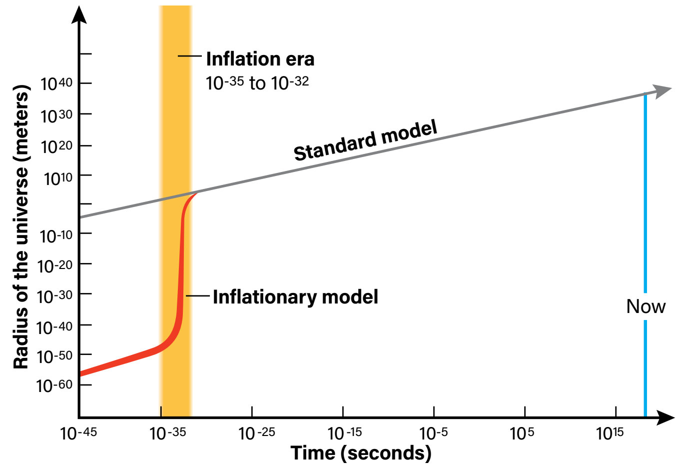
The Big Bang wasn't without its contrivances. As far back as the 1940s, cosmologists recognized serious flaws in the theory's narrative. Furthermore, no one knew what had caused the Big Bang to begin its prodigious expansion. By the 1970s, several fissures had emerged, calling the accuracy of the Big Bang into question.

One was the universe's spatial curvature — a measure of how initially parallel beams of light diverge as they propagate. Our universe is approximately "flat," meaning that the rules you learned in geometry class, such as parallel lines never meet, apply everywhere. This is fortuitous: You might not be reading this if the curvature were otherwise. (See "Exploring the shape of space-time," page 56.)

There are infinite possible curvature values that the universe *might* have had. Yet flatness, or zero curvature, is the most unstable value it can take — any departure from zero would potentially have caused the universe to immediately collapse right after it formed. This would prevent any structures, let alone life, from developing. In 1979, Guth attended a lecture by Bob Dicke, a renowned physicist who, along with Jim Peebles, speculated that

The author and his collaborators used the BICEP telescope (foreground) in Antarctica to search for the imprint of inflation's gravitational waves on the light of the CMB. However, no definitive evidence has yet been found.
HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

AN INFLATIONARY UNIVERSE



This graphic shows the size of the observed universe over time, highlighting differences between inflation (red line) and the standard Big Bang theory (dark gray line). In an inflationary universe, the size of the observable universe starts out small enough that regions that end up far apart after inflation (which occurs during the time shaded out by the vertical yellow bar) can have the same temperature because they were in contact beforehand. This horizon problem is one issue with a Big Bang theory that does not include inflation. *ASTRONOMY*: ROEN KELLY, AFTER ALAN GUTH

the universe's properties, including its flatness, were so crucial to life's existence that there had to be an underlying reason. (Peebles was awarded the Nobel Prize in Physics in 2019 for his work in the field of cosmology.)

Anthropic arguments like these — with no apparent explanation except that otherwise we would not exist to observe the conditions they bring about — are anathema to cosmologists. Guth was inspired to devise a mechanism that *forced* flatness on the universe. He began developing the inflationary universe paradigm in 1979, ultimately publishing it in *Physical Review D* in 1981.

The paper states that cosmic inflation expanded space-time by a factor of 10^{30} over approximately a trillionth of a trillionth of a trillionth of a second. Seconds later, BBN begins, followed by the more familiar Hubble expansion. Inflation puts the "bang" in the Big Bang, courtesy of a strange substance: a field called the inflaton, which acts as a source of antigravity, and propels the universe's exponential, accelerated expansion — albeit only briefly.

Inflation said flatness was not the result of fine-tuning; rather, it was inevitable. When the universe grows by a factor of approximately 10^{30}, any residual spatial curvature left after inflation is negligible. This is consistent with observations of the cosmic microwave background (CMB) radiation — the afterglow of the Big Bang — later obtained by the Millimeter Anisotropy eXperiment IMaging Array (MAXIMA) and Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics (BOOMERanG) experiments in 2000. The most recent combined analysis of CMB and galaxy-clustering data limits the maximum amount of the universe's curvature to be below 0.2 percent.

Inflation said flatness was not the result of fine-tuning; rather, it was inevitable.

Guth's paper also explained the astonishing uniformity of the universe. Observations show that far-flung regions of the cosmos have nearly identical amounts of CMB radiation. In the standard Big Bang scenario, disparate regions had never been close enough to one another for their temperatures to equilibrate. This troubling observation was known as the horizon problem. Inflation solved it by allowing for widely separated regions of the universe to have previously been in contact, reaching a single temperature in a much smaller universe prior to inflationary expansion.

But Guth's model wasn't flawless. It failed to account for how inflation started … or ended. It also lacked a way for structures such as galaxy clusters to form — how could clumps of matter arise after inflation's prodigious flattening? Fortunately, soon after Guth's paper was published, theorists such as Paul Steinhardt, Stephen Hawking, Andrei Linde, and others rectified technical problems in Guth's model. Their solutions included the idea that unavoidable quantum jitters of the inflaton field caused the universe's expansion to vary depending on location. These jitters would result in fluctuations in the universe's matter density, leading to regions where dark matter and ordinary matter clump together to (much later) seed galaxies. Such fluctuations were observed in the CMB in 1992 by the Cosmic Background Explorer (COBE) satellite.

Elusive evidence

With such a successful string of consistent claims, inflation should be widely accepted by all practicing cosmologists, right? Not entirely. There are other models, aside from inflation, that predict the same jitters that would lead

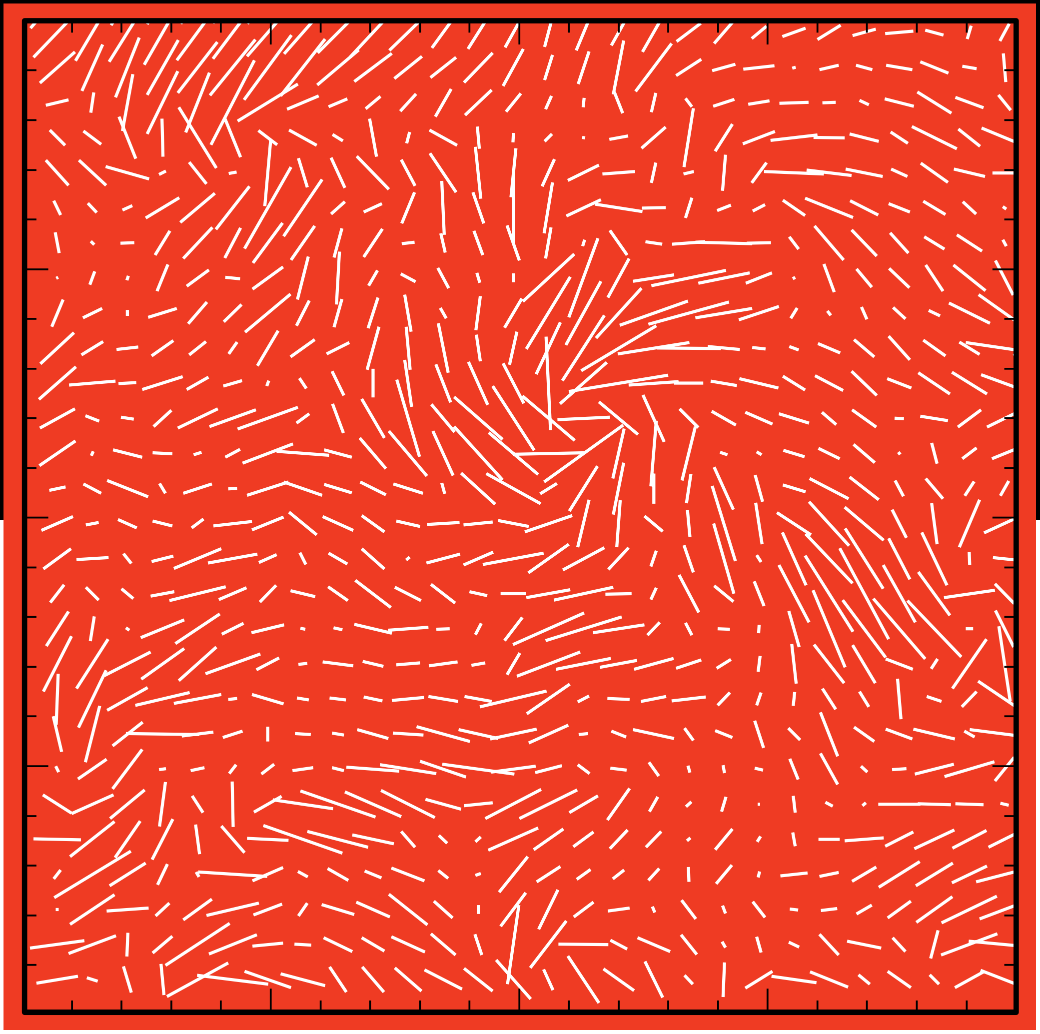
to the large-scale structures observed today.

But inflation's most significant shortcoming is failing to explain how it got started. Even Guth only considered its consequences, *assuming* inflation was somehow initiated. This led some critics to claim that inflation and its consequences aren't testable, which is a major requirement of the scientific method. What is needed is a way to test the unique predictions inflation makes, allowing cosmologists to differentiate between a universe in which inflation took place and alternate theories.

By the early 1990s, cosmologists had found just such a "smoking gun" of inflation. They showed that, if inflation took place, it would inevitably result in primordial gravitational waves. These waves propagate at light-speed, endure forever, and pervade all matter, making them unique messengers of the inflationary epoch. They are the ideal evidence of inflation — if such waves could be detected. If measured, these waves could reveal information about the inflationary epoch much the same way that photons, massless messengers themselves, encode the properties of the cosmos 380,000 years after BBN.

In the early 1980s, Russian physicist Alex Polnarev predicted these gravitational waves would distort space-time in a way that induces specific patterns in the light of the CMB. These patterns in the light's orientation, or polarization, were later called B-modes and their properties fully elucidated by other researchers in the late 1990s. If detected, B-modes would confirm inflation beyond a reasonable doubt. By 2001, my experimental colleagues and I decided to test whether we could detect these inflationary relics. Detecting gravitational waves via their imprint on the CMB's polarization would falsify alternatives to inflation, cementing it once and for all as cosmology's touchstone. But our apparent detection of B-mode polarization using the Background Imaging of Cosmic Extragalactic Polarization, or BICEP2, instrument in 2014 was later retracted. Definitive evidence remains elusive.

B-MODES IN THE CMB



Measuring the polarization, or orientation, of the light from the CMB could reveal whether inflation took place. Primordial gravitational waves produced during the epoch of inflation would have alternately stretched and squished space-time in such a way that at the time the CMB was produced, its light would contain B-modes — a swirling pattern — still visible today. If detected by future experiments, these B-modes would provide a clear signature of inflation, as no source other than cosmological gravitational waves can produce them in the CMB. Above is an example of what B-modes look like in a field of polarized light. *ASTRONOMY*: ROEN KELLY, AFTER WAYNE HU

The search continues

Inflation is consistent with many pieces of cosmological data, but consistency doesn't constitute proof. Several upcoming CMB experiments hope to change that. They include the Simons Observatory, the BICEP Array, and the "Stage-4" CMB-S4 experiment. These efforts will either detect primordial B-mode polarization arising from inflation-generated gravitational waves or drastically winnow the allowable number of inflationary models.

Nevertheless, B-mode detection is not guaranteed. Or inflation may not have happened at all. Frustratingly, many alternatives to inflation are similarly difficult to prove. So, unless the B-modes signals potentially awaiting astronomers are sufficiently big, we might never be able to say for sure whether the universe underwent inflation or not.

To some cosmologists, that would be deflating news. To others, it would fascinate and inspire — impelling us to create more refined models of our cosmic origins.

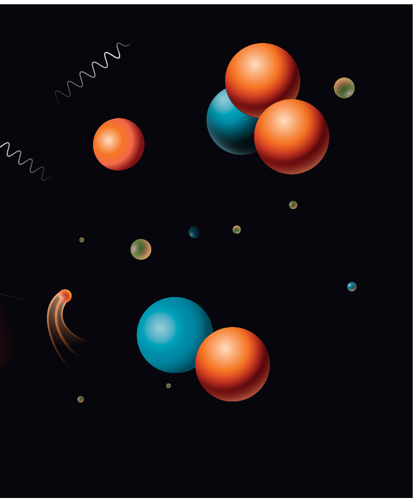
Brian Keating *is a professor at the University of California San Diego, and principal investigator of the Simons Observatory. His book,* Losing the Nobel Prize *(W.W. Norton & Company, 2018), tells the story of the 2014 claim of finding the fingerprints of inflation.*

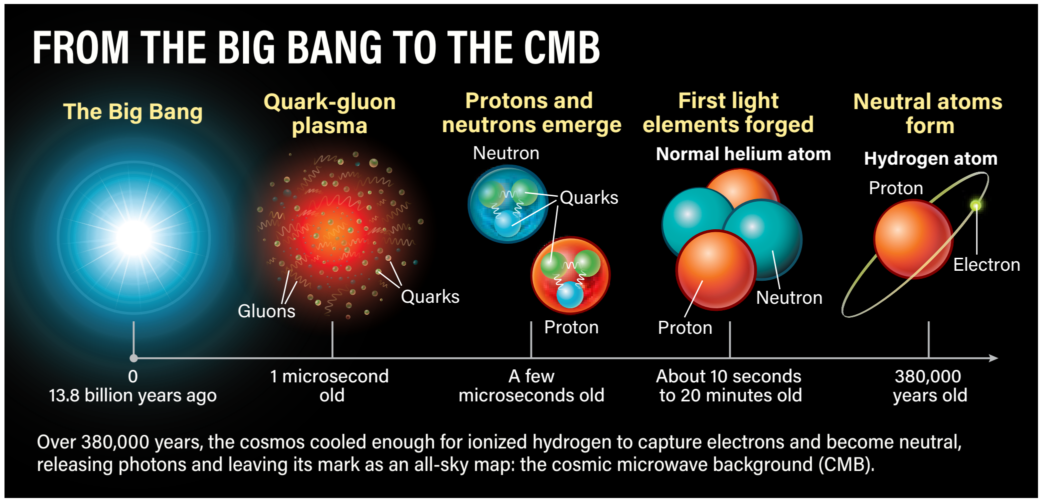
THE EMERGENCE OF MATTER

The universe forged the first elements within minutes of its birth through the process of Big Bang nucleosynthesis. BY CHRISTOPHER CONSELICE

Nearly 2,500 years ago, the Greek philosopher Democritus first proposed that objects are made of countless indivisible building blocks called *atoms* (Greek: *atomos*). However, it wasn't until about 200 years ago, with the work of English chemist and physicist John Dalton, that the modern idea of atoms was developed.

Next came the challenge of learning to identify and distinguish between the various types of atoms. During the 19th century, advancements in spectroscopy — studying light by breaking it down into its constituent components — allowed scientists to discover that specific elements and molecules each have distinct spectral signatures. These signatures reveal themselves through unique combinations of emission and absorption lines (extra light and missing light, respectively) for each element. And by the mid-19th century, shortly after researchers first started classifying elements commonly found on Earth, astronomers began equipping their telescopes with spectroscopic sight to learn what the universe is really made of.





Over 380,000 years, the cosmos cooled enough for ionized hydrogen to capture electrons and become neutral, releasing photons and leaving its mark as an all-sky map: the cosmic microwave background (CMB).

ALL ILLUSTRATIONS: *ASTRONOMY:* ROEN KELLY

One of the obvious celestial targets for early spectroscopes was the Sun. When astronomers observed our star during a solar eclipse, with the Moon blocking most of the Sun's overpowering light, they found a mysterious spectral line that didn't correspond to any element yet known on Earth. The substance was dubbed *helium*, after the Greek word *Helios*, meaning Sun.

Early spectroscopic targets also included stars and planetary nebulae, but eventually, astronomers expanded their sights to include all astronomical objects. Today, we know from studying deep-sky (and, therefore, distant) targets that some common elements found on Earth have existed for almost the entirety of the cosmos' life, created within the first minutes of the universe through the process of Big Bang nucleosynthesis (BBN).

Elemental origins

The universe didn't create all of the elements at the same time, though. And each one has multiple pathways to formation. If we rewind to the very first moments of the universe, we find it was dominated by the smallest atomic building blocks — quarks, electrons, and other fundamental particles. Only later, a few millionths of a second after its birth, did the universe form protons (hydrogen) and neutrons as it rapidly expanded and cooled.

Primordial helium acts as one of many signatures notarizing the cosmos' birth certificate.

Soon after the first hydrogen formed, a couple of heavier elements quickly followed suit. But this process of BBN didn't really kick off until the universe reached an age of just 10 seconds old. And it only lasted as long as 20 minutes.

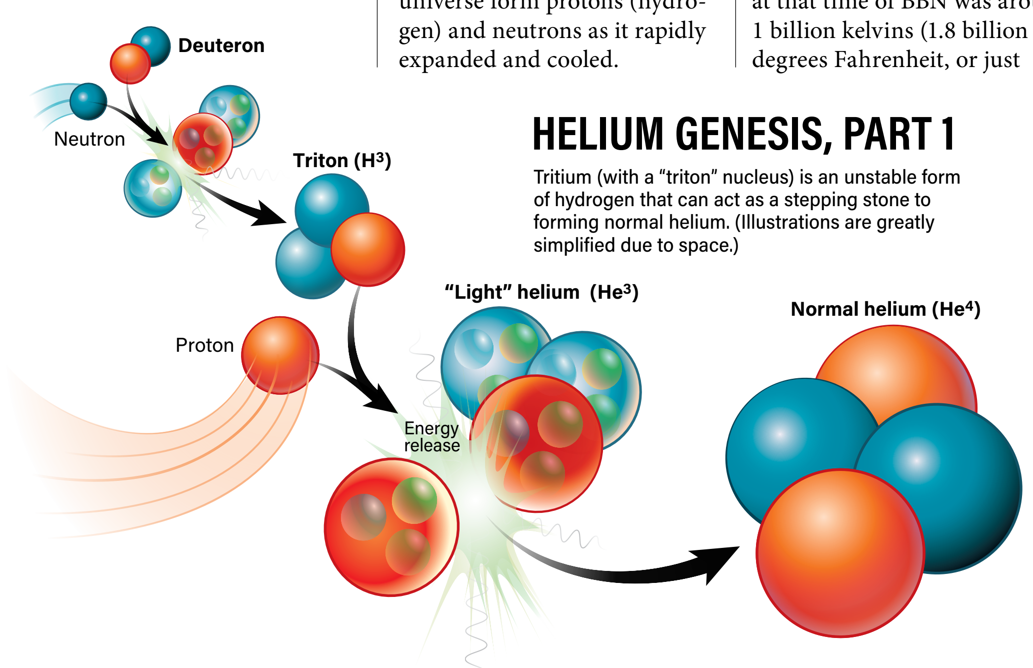
Remarkably, the density of the universe at this time was incredibly low, about 100,000 times less dense than liquid water. If that's the case, though, then why don't we see nucleosynthesis occurring on Earth, where densities are much higher? The answer is that the temperature at that time of BBN was around 1 billion kelvins (1.8 billion degrees Fahrenheit, or just under 1 billion degrees Celsius). Thus, the earliest hydrogen atoms were zipping around so quickly that they frequently collided with great energy, which allowed them to merge into even heavier atoms like helium.

Within the universe's first 20 minutes, it created most of the helium that exists today, as well as deuterium (heavy hydrogen) and a small amount of lithium. Over that same period of time, the ambient temperature of the universe dropped from about 1 billion kelvins to roughly 10 million kelvins, which is roughly the temperature found in the cores of stars, where stellar nucleosynthesis still occurs to this day. So, once the universe cooled down enough, BBN ceased producing the earliest and lightest elements.

Nonetheless, this early epoch saw so much helium created that the element ended up accounting for *about* 25 percent (by mass) of all the matter in the newborn universe. But astronomers want to know *precisely* how much of each element, particularly helium and deuterium, was produced during BBN. That's because knowing these exact values is key to astronomers both confirming and better understanding the generally accepted theory for how the cosmos burst into existence: the Big Bang.

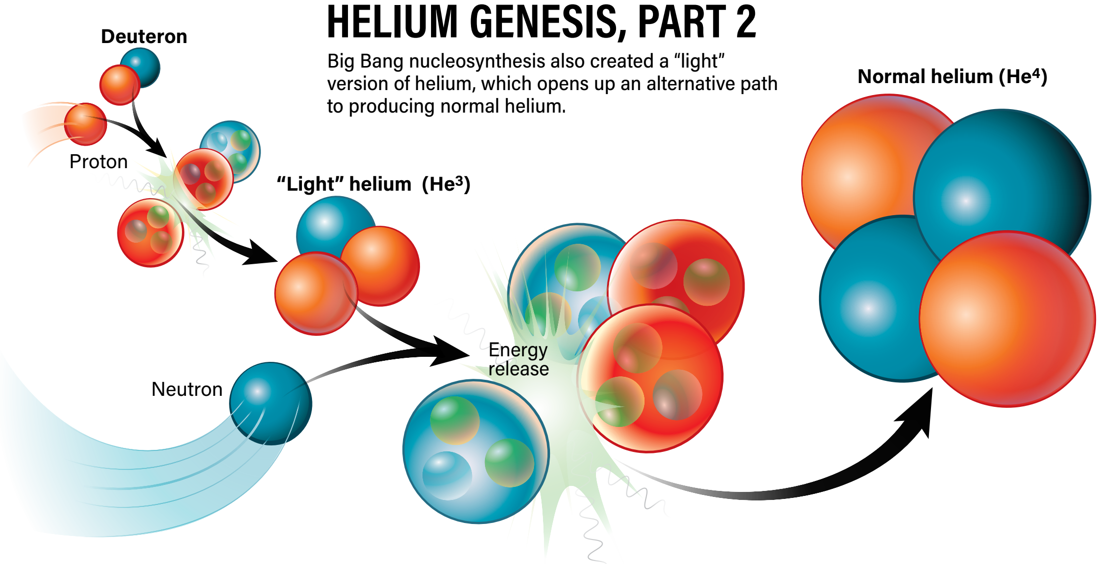
HELIUM GENESIS, PART 1

Tritium (with a "triton" nucleus) is an unstable form of hydrogen that can act as a stepping stone to forming normal helium. (Illustrations are greatly simplified due to space.)



HELIUM GENESIS, PART 2

Big Bang nucleosynthesis also created a "light" version of helium, which opens up an alternative path to producing normal helium.



Forming helium and lithium

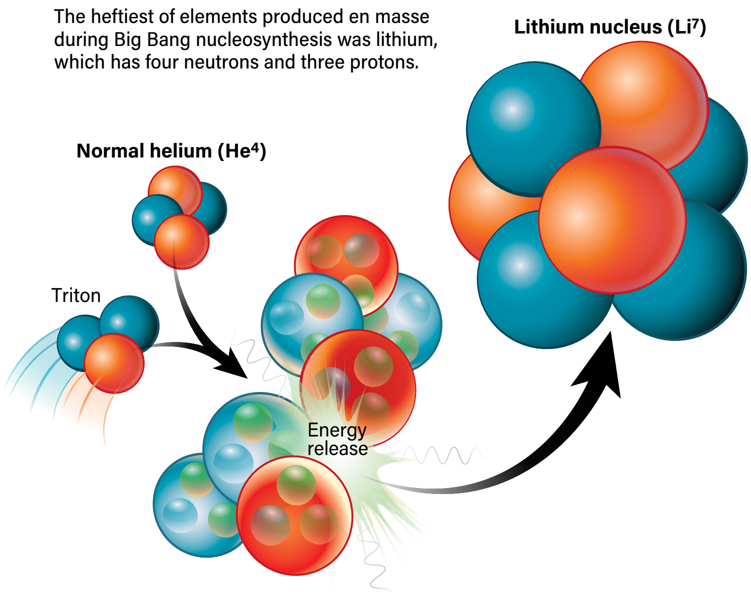
The nucleus of a regular hydrogen atom contains a single proton. But there's a heftier version, deuterium, that can also exist. Deuterium is a hydrogen atom whose nucleus (a deuteron) contains a proton *plus* a neutron. So, although deuterium has the same charge as normal hydrogen, it's about twice as massive. Deuterium is also relatively rare; on Earth, normal hydrogen is about 7,000 times more common than its heavier sibling. But once deuterium is around, it can go on to encourage the production of heavier elements like helium.

There's more than one way to create helium. In the most basic sense, a deuteron and a neutron can join up to create tritium. By then adding another proton to the mix, you get a stable helium-4 atom. Alternatively, a deuteron and a proton can pair up to create a "light" version of helium called helium-3, which has two protons and one neutron. With the addition of another neutron, you get helium-4.

The heaviest element produced during BBN, however, was lithium-7, which, with three protons and four neutrons, follows helium on the periodic table. The early universe didn't form elements heavier than lithium, however. Those were created later in the cores of evolving stars.

LET THERE BE LITHIUM

The heftiest of elements produced en masse during Big Bang nucleosynthesis was lithium, which has four neutrons and three protons.



One of the major successes of the Big Bang theory is that the observed abundance of helium is consistent with what it predicts. The nucleosynthesis process took off when the universe was dense and hot enough to join protons and neutrons into light atomic nuclei. But if the infant cosmos had been more densely packed with matter, then nucleosynthesis might have gone into overdrive, perhaps forming even heavier elements.

Similarly, if the expansion rate of the early universe were slower than theory predicts, then it would have remained in a dense state for a longer period of time, producing more light elements. If either of these things — matter density or expansion — were different than the Big Bang theory says, we would observe more helium than we see today. In other words: Primordial helium acts as one of many signatures notarizing the cosmos' birth certificate.

Confirming our creation

It's incredible that cosmologists can calculate the specific abundances of elements produced during BBN, then compare those predictions directly to the data. But, of course, one has to wonder whether our data really capture a pristine snapshot of the untainted abundances of elements that existed shortly after the Big Bang. Stellar nucleosynthesis surely leads to some contamination, but exactly how much remains an open and pressing question.

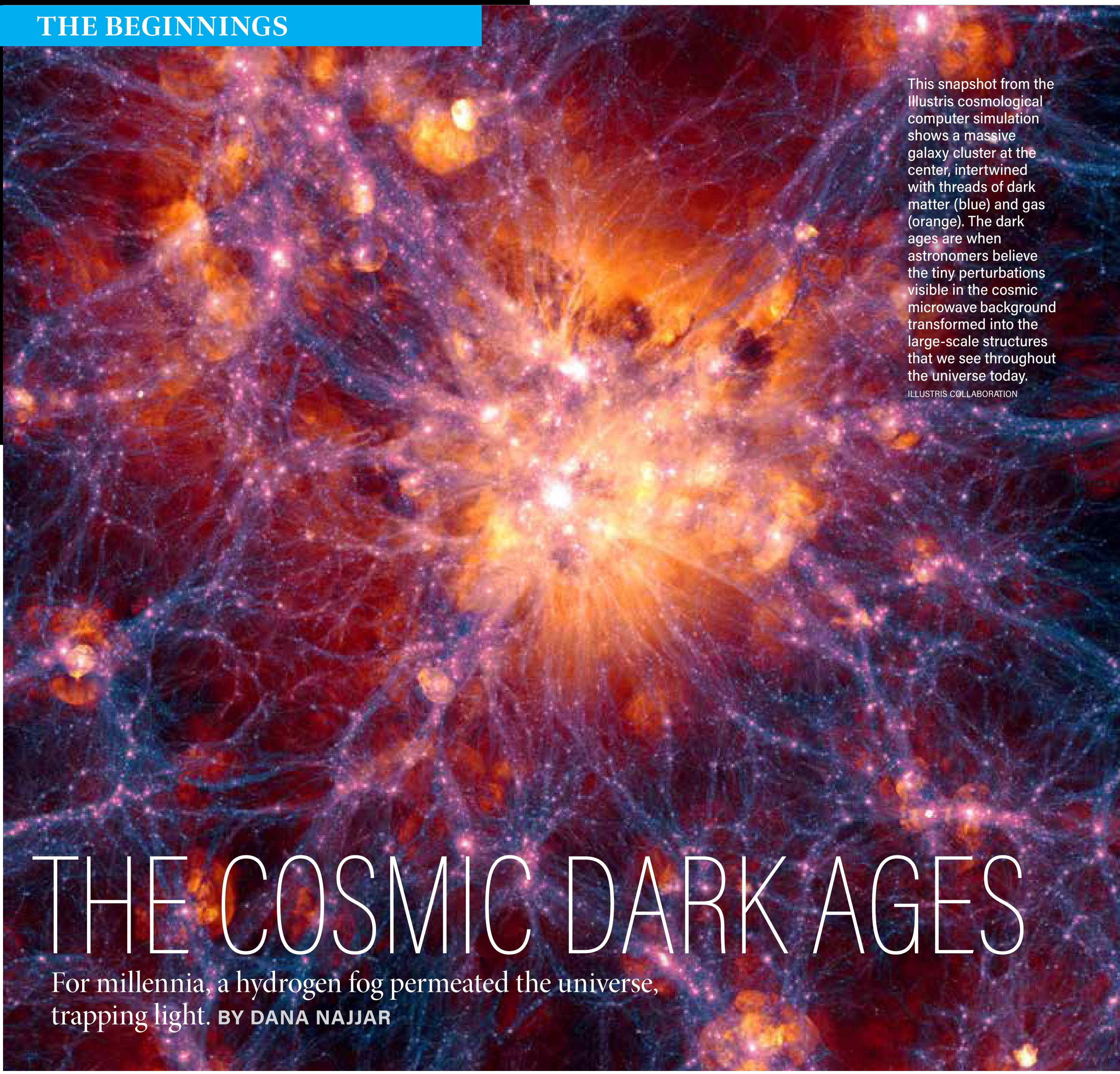
Fortunately, astronomers can observationally measure the abundances of important elements in a variety of ways. The most deterministic is to seek out deuterium and helium. This is often done by examining their prevalence in large pockets of quiescent gas around quasars, whose elemental compositions reveal themselves through absorption lines in their spectra. Because these gas clouds are largely devoid of stars, they're expected to have experienced very little stellar evolution. They are ancient, relatively pristine cosmic relics. And when measuring the abundances of deuterium and helium in these clouds, astronomers find they line up with what Big Bang theory predicts.

This is largely seen as a wonderful confirmation of our universe's origin story, as well as the entire process of Big Bang nucleosynthesis. But it's also a fantastic example of how astronomy enables scientists to probe the very earliest moments of the universe, during the brief period of time when the first matter was being forged.

STARDUST

Stellar nucleosynthesis creates helium from hydrogen, which is then converted into carbon and heavier elements within stars. During supernova explosions, these elements are dispersed into the cosmos, complicating things for astronomers who are trying to calculate the primordial abundances of elements based on modern observations. —*Jake Parks*

Christopher Conselice *(@conselice) is a professor of extragalactic astronomy at the University of Manchester in England.*



This snapshot from the Illustris cosmological computer simulation shows a massive galaxy cluster at the center, intertwined with threads of dark matter (blue) and gas (orange). The dark ages are when astronomers believe the tiny perturbations visible in the cosmic microwave background transformed into the large-scale structures that we see throughout the universe today. ILLUSTRIS COLLABORATION

THE COSMIC DARK AGES

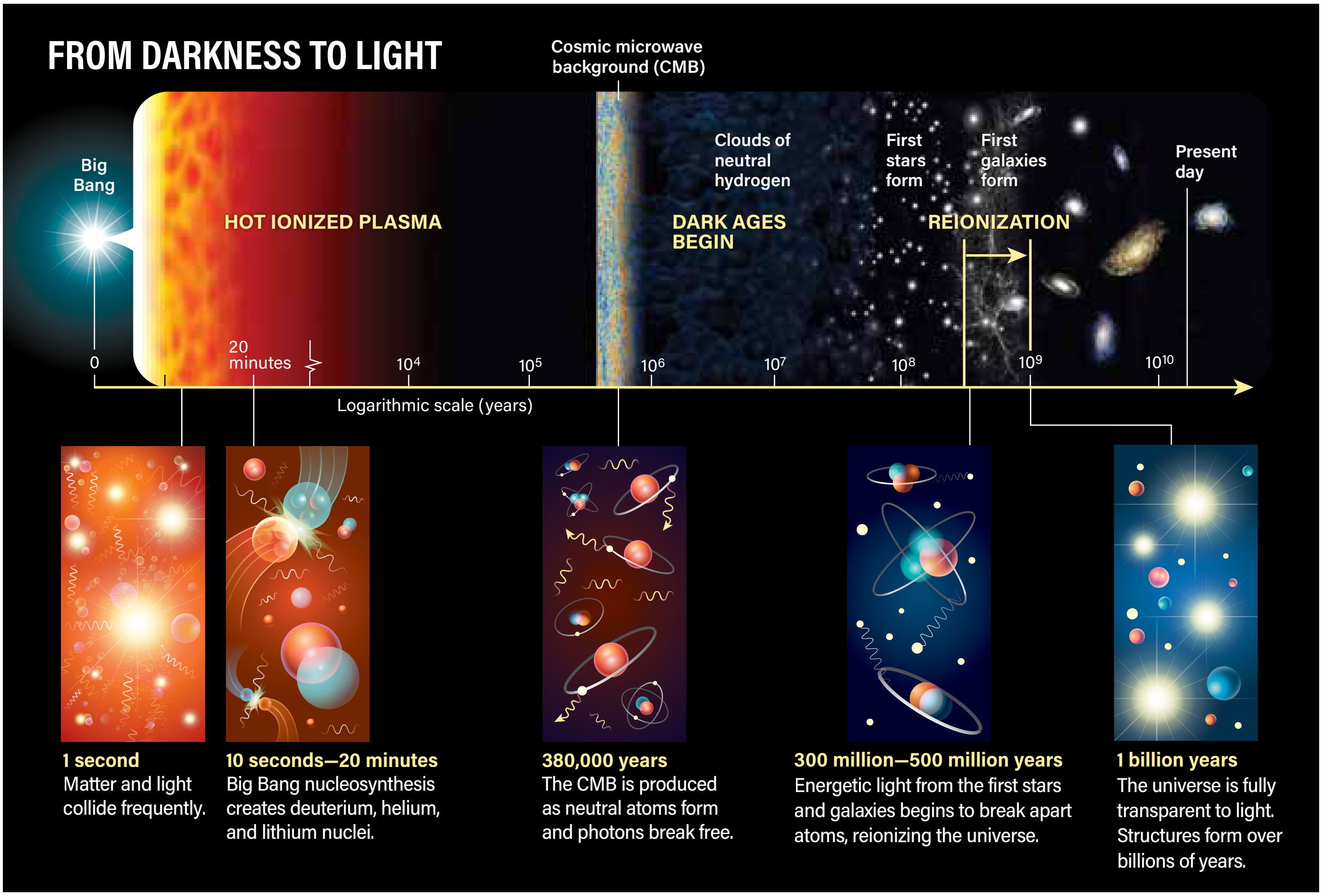
For millennia, a hydrogen fog permeated the universe, trapping light. BY DANA NAJJAR

The early universe was a place of extremes. It was inconceivably small and scorching, with all the energy and matter there would ever be crammed into a tiny space a billion times hotter than the center of the Sun. In the first moments after the Big Bang, the universe cooled enough to allow fundamental particles — such as quarks and electrons — to spring into being. Quarks combined to form protons and neutrons and, not long after, the nuclei of deuterium, helium, and lithium were formed. Energy zipped around the infant universe in the form of photons, but that early light ricocheted off free electrons, which weren't yet bound to any atom, at every turn.

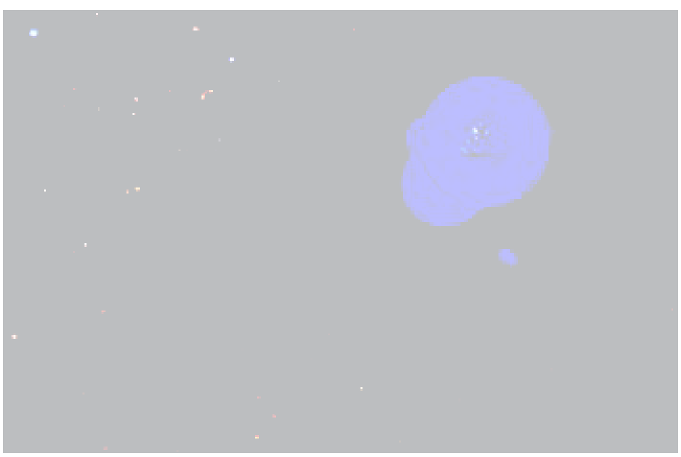
Fast-forward another 380,000 years, and the universe had cooled enough to allow the early nuclei to pull in electrons and form neutral atoms. (This is called recombination, although it actually marks the first time these particles combined.) This moment ushered in darkness — a period we now call the cosmic dark ages.

Seeing the universe

Looking at an object, either with our eyes or with a telescope, requires photons of



ASTRONOMY: ROEN KELLY



The three galaxies (circled in green) that form the EGS77 galaxy group are glowing just 680 million years after the Big Bang. These galaxies have been observed ionizing the atoms around them, generating overlapping bubbles of ionized hydrogen (depicted by an artist in the inset). Astronomers believe that as more galaxies formed over time, such bubbles grew and eventually overlapped throughout the universe, bringing the dark ages to an end. NASA, ESA AND V. TILVI (ASU)

light to hit some sort of detector, whether it's your retina or a camera. But the cosmic dark ages were a time when the universe was enveloped by a fog of neutral hydrogen that trapped the light of the first stars and galaxies. The fog didn't lift until 1 billion years after the Big Bang, when the neutral hydrogen had been reionized and once again split apart. Because light couldn't escape its surroundings during the dark ages, it couldn't journey outward through the universe to hit our detectors here on Earth, nearly 13 billion years later. As a result, trying to peer back at that time is like trying to see a lightbulb through a thick, dark haze.

But interesting things were happening, even if we can't see them. Think of our own Dark Ages here on Earth, between about A.D. 500 and 1000. It may not seem like much happened in terms of scientific or cultural advancement, but stirring beneath the surface were forces that would set in motion the Renaissance. Similarly, the cosmic dark ages were a time of great transformation.

"This period is special in the sense that it marks the transition between the universe being very simple and being very complex," says Avi Loeb, an astronomer at the Harvard-Smithsonian Center for Astrophysics who was among the first to explore this time in the early universe. "Black holes, neutron stars, even life eventually here on Earth … the roots of it were planted at the dark ages. If we want to understand where we came from, that's where the story starts."

Astronomers do know what the universe was like just before the dark ages began. That's because they have an actual image of what conditions were like at that time. When the first neutral atoms formed, the process released photons of light that set off across the universe, creating a cosmic snapshot of the exact conditions at the beginning of their journey. This cosmic microwave background (CMB) radiation, also known as relic radiation, exists all around us today and tells astronomers that the universe was more or less uniform in density at that

time, with only very small ripples in it.

But those ripples are important. "If you feed those perturbations into a computer simulation, you get objects like galaxies we see today," says Loeb. "The dark ages mark the transition that the universe made from these small fluctuations into objects, the first galaxies, the first stars. That's a major transition."

The precise way in which that transition happened is still poorly understood. What astronomers do know with certainty, however, is why we can't see any light from objects shining during the dark ages. For starters, there wasn't much light before the first stars formed. Aside from hydrogen atoms, most of the universe was made up of dark matter, which doesn't emit light.

What's more, a cosmic fog of neutral hydrogen atoms permeated the universe, scattering or absorbing many of the ultraviolet (UV) photons that the very first stars emitted. "The time it would take for a photon to escape [the hydrogen] was longer than the age of the universe," explains Bahram Mobasher, a professor of physics and astronomy at the University of California, Riverside. So, light can't reach us from that time, however long we wait for it to arrive.

Cosmic dawn

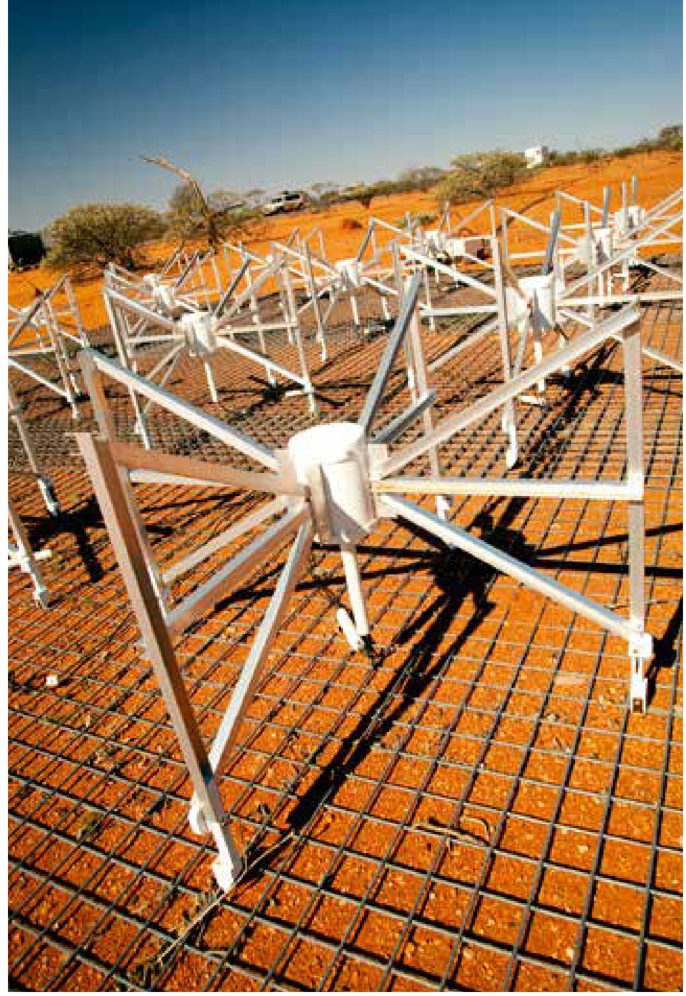
But the dark ages didn't last forever. The story of how the universe once again became transparent to UV light is closely tied to the formation of the first stars and galaxies — several hundred million years after the Big Bang — when matter clumped together and began to form the structures that permeate the universe today. Some of the first stars were massive and bright, their light energetic enough to knock the electrons out of the surrounding hydrogen atoms in a process known as ionization. And ionized hydrogen doesn't absorb or scatter light the way neutral hydrogen does.

"The first stars and galaxies formed, and their light brought the universe out of the dark ages," says Mobasher. That's because the newly born stars and galaxies ionized ever-expanding bubbles around them, allowing light to finally travel unimpeded again.

Although astronomers can't see into the cosmic dark ages, they can observe the light from these early galaxies as they brought about an end to the darkness. Mobasher and his team were part of an international effort to observe some of the farthest galaxies ever recorded. "What we do is look for galaxies at the end of the dark ages," he explains. "That's the most distant object in the universe we can find." Using data from the Cosmic Deep And Wide Narrowband (or Cosmic DAWN) Survey, Mobasher and his colleagues published a paper in *The Astrophysical Journal Letters* in February 2020 identifying a group of galaxies in the process of ionizing the hydrogen around them some 680 million years after the Big Bang. This fits squarely into the time theorists think the epoch of reionization took place, between a few hundred million and 1 billion years after the Big Bang.

"The first stars and galaxies formed, and their light brought the universe out of the dark ages."

By studying this cosmic dawn, Mobasher hopes to answer fundamental questions about our universe today. Understanding the dark ages "would help us understand how galaxies are formed, how stars are formed, the evolution of galaxies through the universe," he says. "How our own galaxy started, how it was formed, how fast it built up stars … all those questions are important questions we need to answer."



The Murchison Widefield Array (MWA) in Western Australia is a precursor to the Square Kilometer Array. Its radio receivers are designed to pick up emission from neutral hydrogen during the era of reionization. Just one of the MWA's 256 tiles is pictured here. AUSTRALIAN SKA OFFICE

It's worth remembering that not all light would have been absorbed by hydrogen atoms during the cosmic dark ages. A hydrogen atom can only absorb light at discrete wavelengths that correspond to the energy required for its electron to jump from one energy level to the next. So, some photons with energies greater than that needed to bump an electron between energy levels would have found their way out of the fog.

To find this light, though, we need a new generation of detectors that are just coming online, like the James Webb Space Telescope, the Hydrogen Epoch of Reionization Array in South Africa, and the Square Kilometer Array in South Africa and Australia.

The reason these infrared and radio telescopes are required is because as light makes its way over time across our expanding universe, it gets stretched out. Even the light emitted in the far ultraviolet range of the spectrum by the first stars reaches us today as light with a much longer wavelength than it began with.

These new facilities will give us a fuller picture of the epoch of reionization — the break of cosmic dawn. Loeb is hopeful these detectors will unlock the vast mysteries of that time: "We will be able to see the history of things take place during reionization," he says. "The coming years will be very exciting."

Dana Najjar *is a journalist and software developer whose work has also appeared in* Scientific American *and* Popular Science. *She holds a bachelor's in physics from MIT and a master's in science journalism from NYU.*

THE BEGINNINGS

This artist's impression depicts CR7 — one of the oldest known galaxies, discovered by the European Southern Observatory's Very Large Telescope in 2015. Dating to just 800 million years after the Big Bang, it likely contains examples of the universe's very first generation of stars. ESO/M. KORNMESSER

THE FIRST STARS ARE BORN

They lived fast, died young, and seeded the cosmos with material for future generations. **BY MICHAEL E. BAKICH**

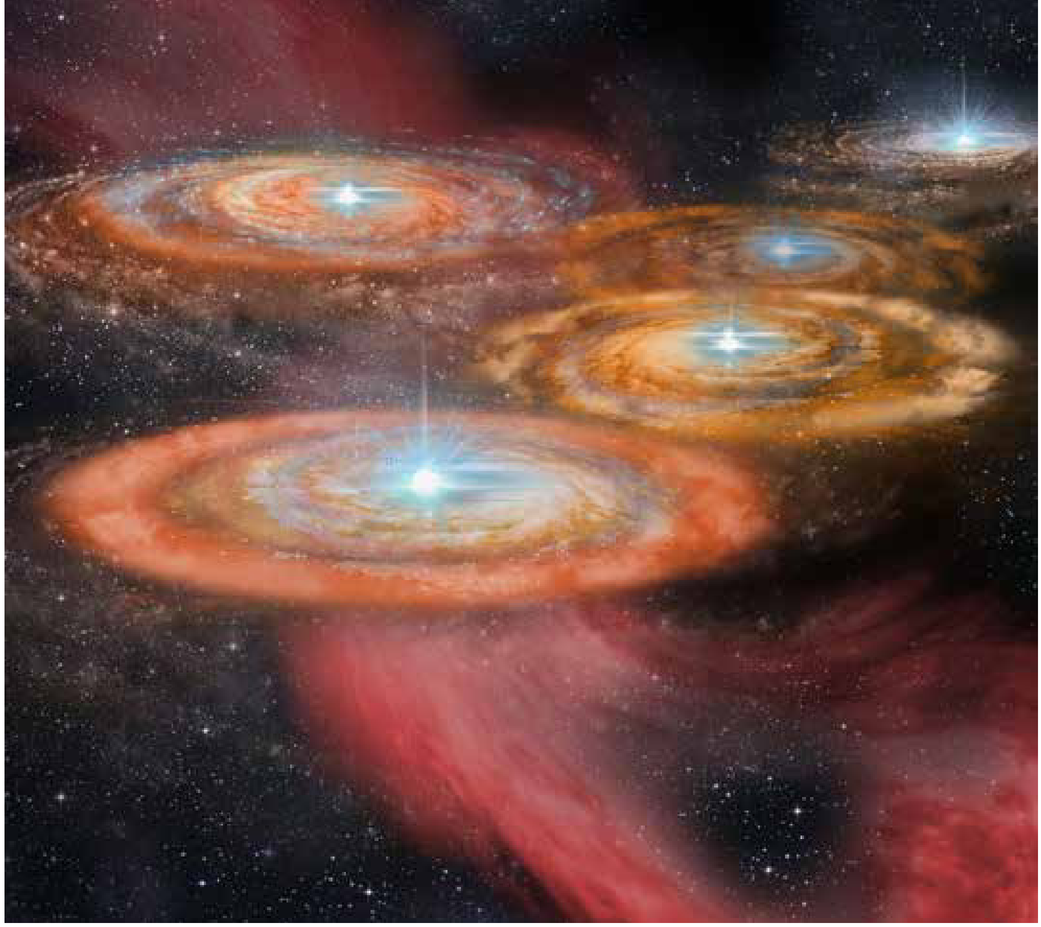
For 380,000 years after the Big Bang, the cosmos was a hot, dense mixture of protons, electrons, other elementary particles, and light elements. But the expanding universe was cooling fast. And once the temperature dropped to about 4,950 degrees Fahrenheit (2,730 degrees Celsius), protons and electrons were able to form atoms.

Not all atoms, mind you. No gold was floating around, or aluminum, or even elements as light as oxygen. Hydrogen and its heavy isotope deuterium accounted for about three-quarters of everything. A couple of isotopes of helium accounted for most of the other quarter. And a tiny fraction (about one-billionth of everything) of lithium had also been produced.

Just because brand-new hydrogen and helium were swirling about doesn't mean stars were popping into existence. In fact, the first of those luminous objects didn't appear until the universe was about 100 million years old. So, for a span of time longer than the dinosaurs have been extinct on Earth, there were no stars or galaxies, or, for that matter, any objects emitting light.

It's out of this darkness that astronomers are trying to piece together the origin of the first

generation of stars, called Population III stars. As brightly as they shone, their light is now too faint to be detected by current observatories — and even the next generation of telescopes will struggle to spot them. But through scientific detective work, astronomers are beginning to understand how these elusive objects lived and died.



A cluster of five of the universe's first stars, sheathed in disks of gas, is taking shape in this artist's illustration. These stars would have been much hotter and more massive than the Sun. SHANTANU BASU, UNIVERSITY OF WESTERN ONTARIO

The universe lights up

A major clue comes courtesy of the cosmic microwave background (CMB), the relic radiation that formed in the hot, early universe. This radiation has been cooling ever since it was emitted as the cosmos expands — currently, the background temperature is about 2.73 kelvins (–455 F, –270 C). And measurements of the CMB show that it is incredibly consistent, corresponding to density variations of only 1 part in 100,000. But those variations, literal ripples in the structure of the universe, are revealing how the first stars formed.

Computer models show that the minuscule density fluctuations in the early universe acted as starting points for immense clouds of gas. Without these variations in structure, nothing would have formed. The whole cosmos would have evolved into an ever-thinning homogeneous cloud of hydrogen, helium, and that tiny bit of lithium. Thanks to gravity, however, the fluctuations became gathering points: huge clouds where gas continued to collect. Eventually, the clouds contracted. As they did, they heated up to more than 1,300 F (700 C).

Gas and dust glow brightly as they fall towards the supermassive black hole at the center of one of the universe's first galaxies, in this artist's concept. NASA/ESA/ESO/WOLFRAM FREUDLING ET AL. (STECF)

That temperature would be far too high for a star-forming region today to form stars. Indeed, if a cloud is hotter than about 10 kelvins (–442 F, –263 C), the speed of the atoms inside it will be too fast for them to stick together and eventually form stars.

But the clouds in the early universe were larger and much more densely packed than modern-day nebulae. Within them, some hydrogen atoms paired up to become hydrogen molecules. And because molecules are better emitters of infrared radiation (heat), the temperature dropped and clumps inside the clouds could contract further.

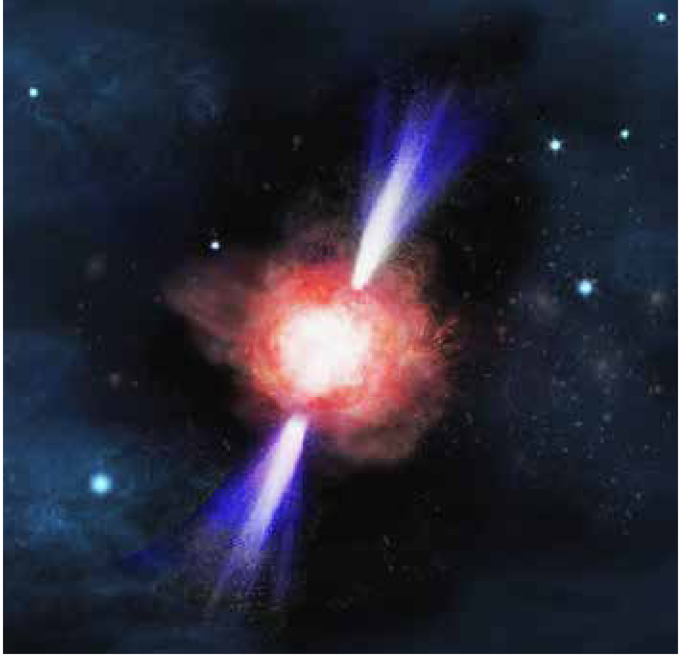
Each of the regions was probably several hundred times as massive as the Sun. That much mass, and its corresponding gravity, could overcome the outward pressure from radiation. The clumps didn't split as they contracted, so only a single star formed from each one. The result was that the first stars were potentially colossal — estimates range from several tens of solar masses up to 1,000 solar masses — and luminous, perhaps millions of times as bright as the Sun.

Because the universe was smaller and denser, vast numbers of these stars formed near each of its density variations. Eventually, the gravitational pull from these stars would attract other stars, and the numbers grew from there. Astronomers think this took a few hundred million years, but, at the end of that time, the first galaxies had formed.

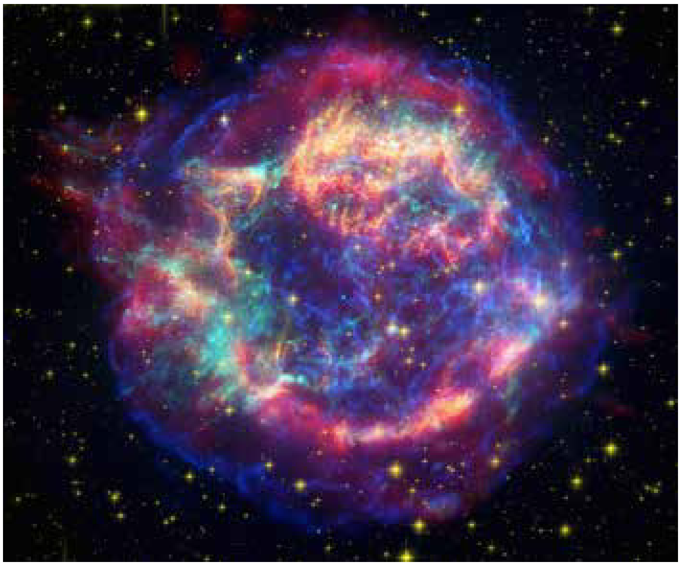
A first star's life

You may be wondering how anyone could figure out how stars formed during a time when the universe was unobservable. Fortunately, the cosmos wasn't as complex then as it is now, making it simpler for cosmologists to model.

For example, they don't have to account for shock waves



A Population III star goes supernova in this artist's concept. Explosions like these produced heavier elements and spat them out into the universe. KAVLI IPMU



Astronomers have detected phosphorus in the supernova remnant Cassiopeia A, seen here in false color by three NASA space telescopes. NASA/JPL-CALTECH/STSCI/CXC/SAO

from supernovae compressing the material within distant nebulae. All available material was one of the three lightest elements. There wasn't even any dust yet to affect how the clouds cool.

Astronomers theorize that, in addition to being massive, the first stars also were extremely hot. Their surface temperatures may have been 15 to 20 times that of the Sun, and most of the radiation they emitted was in the ultraviolet region of the spectrum.

And although supernovae didn't play a part in the births of the first stars, such events were a part of all of their deaths. The more massive a star, the quicker it passes through its life, so the first stars may have lived only a few million years or less.

Theory predicts that when a star with a mass between 140 and 260 times that of the Sun reaches the end of its life, it produces a pair-instability supernova. In the core of such an object, electron-positron pairs upset the balance between outward radiation pressure and the inward pull of gravity.

As gravity starts to win this tug-of-war, the core collapses. That, in turn, raises its temperature and causes a huge increase in fusion — so much, in fact, that the star blows up completely, without leaving behind any stellar remnant (such as a black hole). In this way, all the elements the star had synthesized, up to and including iron, are blasted into space. This seeds the surrounding gas with material, creating the mixture that would form future generations of stars. So, in one sense, the deaths of these stars are as important for the development of the universe as their births.

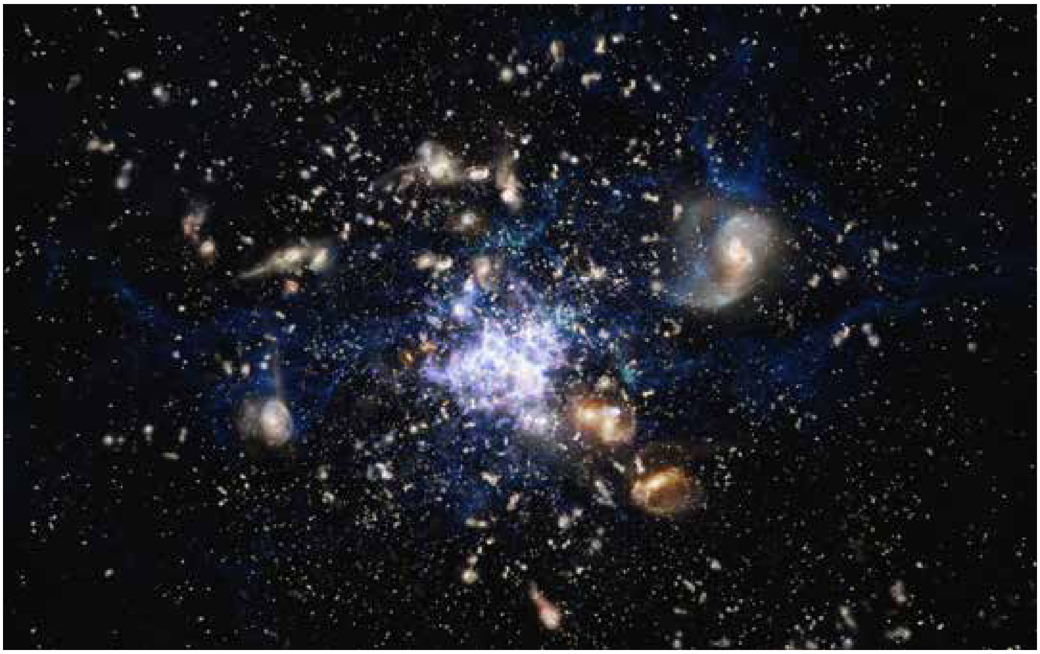
Is dark matter involved?

According to theoreticians, our part of the universe — what we can see and touch — accounts for only 5 percent of the total. The rest is either dark energy (about 69 percent) or dark matter (26 percent). Dark energy does its own thing, which seems to be accelerating the expansion of the universe.

Dark matter also doesn't interact with normal matter — except through gravity. So, although it's impossible to see directly, astronomers can detect it indirectly.

Some scientists now think that dark matter's gravitational tug was crucial in pulling normal material together into clumps and patches (the density fluctuations in the CMB) in the years following the Big Bang. These objects, called dark matter minihalos, would have to have been massive — on the order of a million Suns or more.

Normal matter would have



A cluster of galaxies, gravitationally bound, begins to form in the early universe in this artist's concept. ESO/M. KORNMESSER

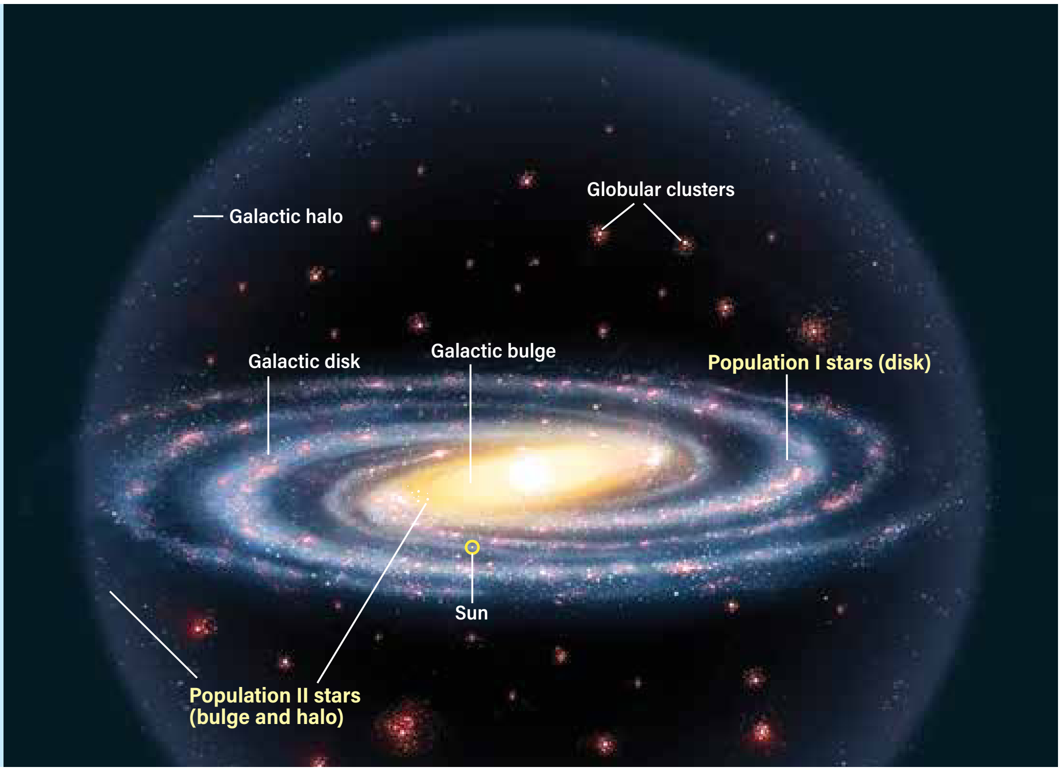
STELLAR DEMOGRAPHICS

Astronomers group stars into three main populations according to their metallicity. Because the proportion of metals in the universe has grown over time, a star's metallicity also hints at its age.

Population I. Metal-rich stars that tend to be young and are found primarily in the disks of galaxies. The Sun is a Pop I star.

Population II. Metal-poor stars that are older and found in the galactic halo and bulge.

Population III. The first generation of stars, made of primordial gas containing almost no metals at all.



ASTRONOMY: ROEN KELLY

needed the gravity of that much mass to overcome the speed of the atoms as the star-forming cloud contracted and heated up. If the minihalo were too small, the atoms wouldn't merge to eventually form stars.

The next best thing

No telescope — on Earth or in space — is currently powerful enough to detect the light of a Population III star. But some scientists think that evidence of what the first stars were like lies a lot closer. They are looking for the second generation of stars, concentrating their search in the Milky Way's halo, a spherical region of old stars and globular clusters — Population II stars — centered on our galaxy's core.

Unlike the Milky Way's disk, which has abundant gas and dust and is filled with young stars — called Population I stars — no new stars are forming in the halo. Compared to the Sun, Pop II stars in the halo contain a smaller fraction of metals — a term that in astronomy refers to any element heavier than helium. And some hyper-metal-poor (HMP) stars might provide clues to unravel how the first stars lived and died because their atmospheres haven't changed much since they formed.

The first two HMP stars discovered were HE 0107-5240 in the constellation Phoenix in 2002 and HE 1327-2326 in Hydra in 2005. Each has only 0.001 percent or less of the Sun's total iron abundance.

In 2019, Rana Ezzeddine, then at MIT (now at the University of Florida), and her team found observational evidence that HE 1327-2326 probably formed in a region of the early universe that had been enhanced by the supernova explosion of a first star with a mass 25 times that of the Sun.

The more massive a star, the quicker it passes through its life, so the first stars may have lived only a few million years or less.

The lowest known iron abundance belongs to the star SMSS J031300.36-670839.3 in the small constellation Hydrus. Discovered in 2014, this star lies 6,000 light-years away. At 13.6 billion years old, it is the oldest star whose age has been determined accurately, and probably one of the earliest second-generation stars to have formed.

To the hunt

For now, astronomers' best hope of directly detecting a Pop III star could lie with NASA's James Webb Space Telescope (JWST), which is scheduled to launch in October 2021. Although its 6.5-meter mirror will be unable to reveal one of the first stars on its own, it could get lucky. Perhaps it could catch an ultra-faint flash that signals one of the first stars becoming a supernova.

Or, if a large galaxy cluster comes in between a Pop III star and JWST, it might act as a gravitational lens, bending and magnifying the light of the star. A 2018 study led by researchers at Arizona State University and the University of Melbourne found JWST might be able to find a few of these first stars if it monitors 30 galaxy clusters twice a year over its estimated lifespan of five to 10 years.

Of course, researchers can dream of building a giant telescope so powerful it could capture the light of Pop III stars unaided.

How fanciful is this prospect? Anna Schauer and her colleagues at the University of Texas calculate that a telescope with a mirror 100 meters wide would suffice — if it were placed on the Moon, that is. Their proposed observatory, dubbed the Ultimately Large Telescope and posted in an online preprint last July, would lie in the eternal shadow of a lunar crater at the Moon's South Pole, isolated from heat that could interfere with its infrared observations.

Could that happen soon? Yes — at least astronomically speaking.

Michael E. Bakich *is a contributing editor of* Astronomy.

HOW TO BUILD A GALAXY

About 13 billion years ago, our galaxy formed in the wake of the Big Bang.

BY MICHAEL E. BAKICH

The Milky Way arcs over the forest of Yosemite National Park in California. CASEY HORNER

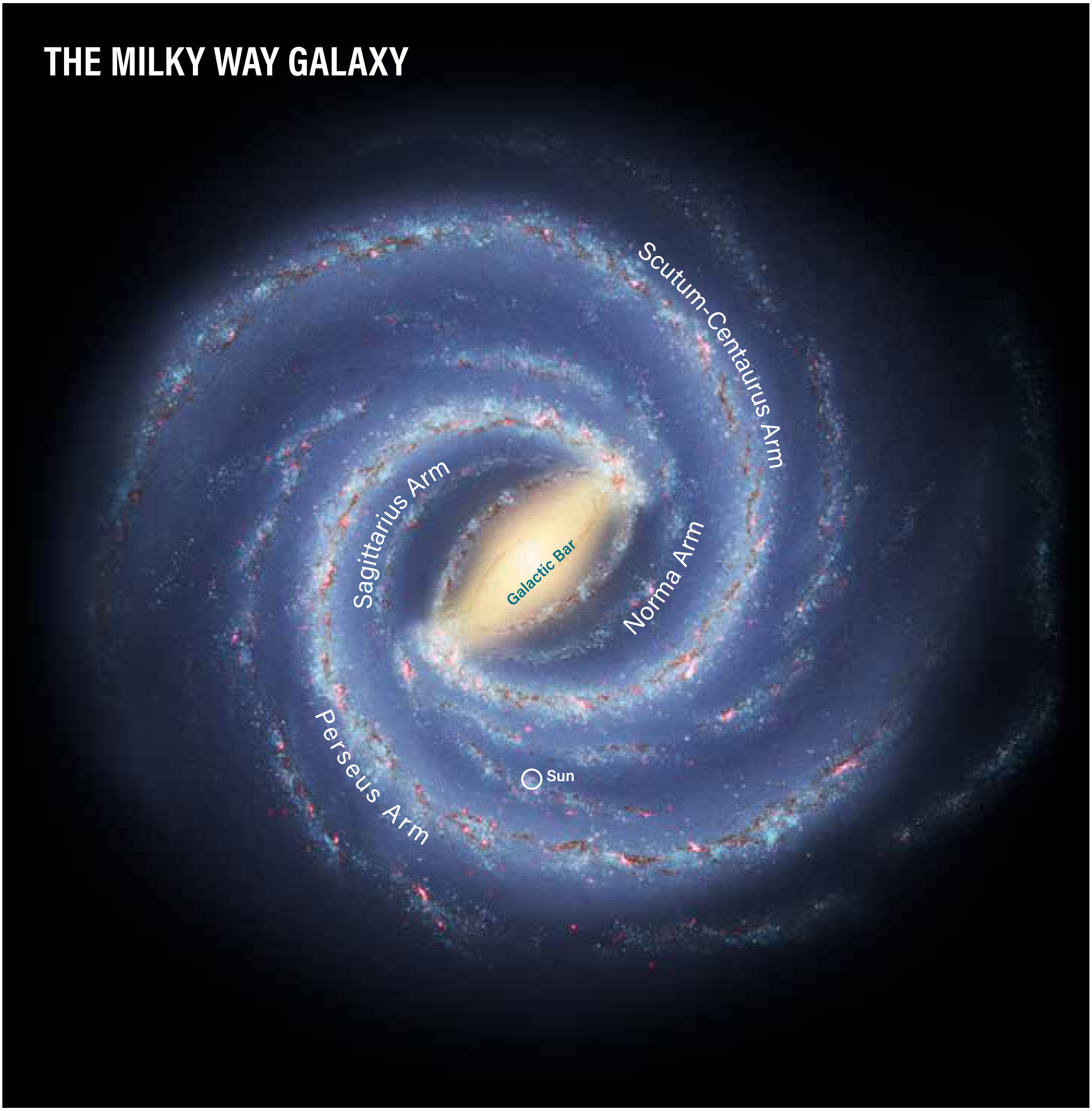
From a dark site on a clear winter night, the sky in the Northern Hemisphere is dominated by a fuzzy band of light that's been called the Milky Way for more than 2,000 years. Starting in the north, its densest section winds through the constellations Perseus, Auriga, Taurus, Gemini, Monoceros, Canis Major, and Puppis, before disappearing beneath the southern horizon.

Point a telescope in its direction and you'll confirm what Italian astronomer Galileo Galilei saw through his first instrument: The Milky Way is made of countless stars. Of course, the past 400 years have revealed other features as well. Among them are bright and dark nebulae, star clusters, and the fading remnants of dead suns. For much of those four centuries, astronomers focused their efforts on surveying our galaxy. They learned its size, shape, mass, motion, and lots more. Yet one big question remains: How did the Milky Way form?

Top-down or bottom-up?

Historically, there have been two general lines of thought about how galaxies form.

The first to take hold was the "top-down" model of galaxy formation. This scenario posits giant sheets of matter formed first, and then later broke up into smaller, galaxy-sized units that collapsed to the familiar disk structures we see today. The earliest top-down model of

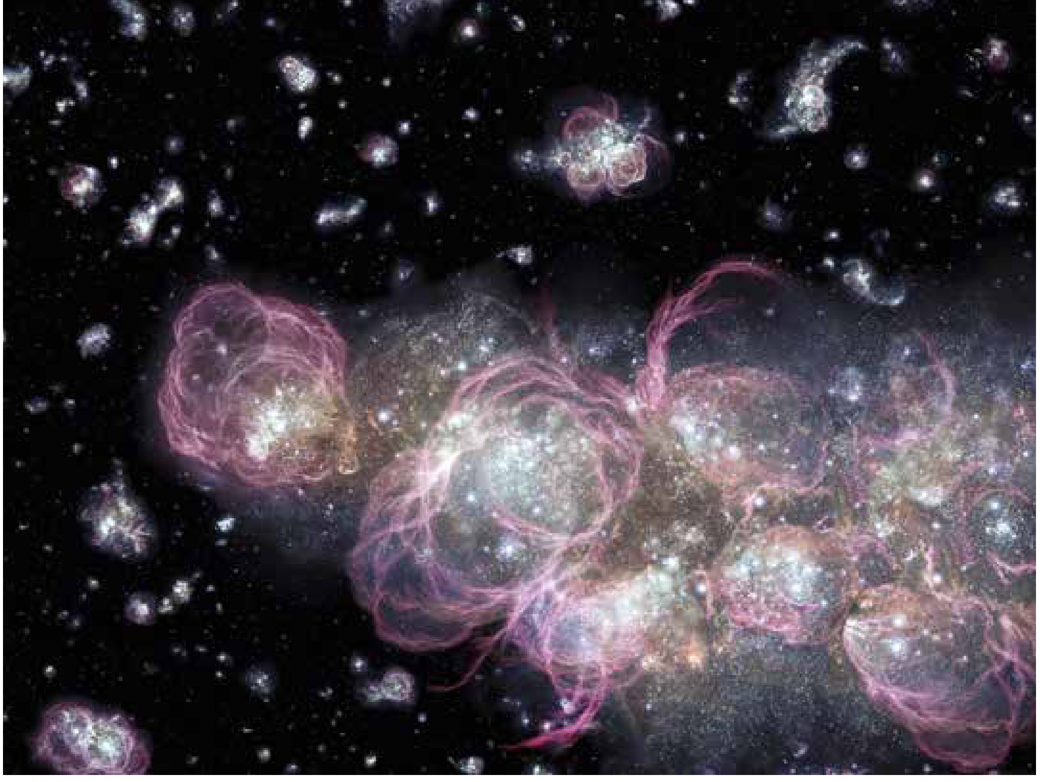


This is the Milky Way, as best we can map it from our vantage point within it. It's dominated by two major arms — the Perseus Arm and Scutum-Centaurus Arm — and has several other minor arms. NASA/JPL-CALTECH/R. HURT (SSC/CALTECH)

galaxy formation appeared in 1962. It's usually referred to as ELS, because the scientists who developed it were American astronomer Olin Jeuck Eggen, British astrophysicist Donald Lynden-Bell, and American astronomer Allan Sandage.

But thanks to evidence from powerful modern telescopes, the vast majority of galactic researchers now think it's more likely the Milky Way formed in a "bottom-up" fashion. This model describes the unions of protogalaxies — smaller blobs of gas that evolved into dwarf galaxies in the early universe and merged with each other to form larger galaxies.

Evidence that mergers are the primary way to form galaxies comes from the Hubble Deep Field Project, started in 1995, and its follow-up efforts, which sought to make the most sensitive images ever in visible light. These images of otherwise-nondescript patches of sky show distant galaxies and numerous bloblike objects that appear to be protogalaxies. Scientists think these fragments merged to form the larger galaxies that we now observe. If this is correct, the Milky Way probably formed when gas clouds and star clusters in the early universe came together to create the galaxy's core. Some researchers believe the Milky Way may have grown from the mergers of 100 or more small galaxies over time.



Protogalaxies burst with stars and bubbles of gas from supernovae and stellar winds in this artist's illustration of the early universe. ADOLF SCHALLER FOR STSCI

Another bottom-up theory states that many dark matter halos, each with about the mass of a globular cluster, formed after the Big Bang. Through gravity, these halos merged and attracted baryonic (normal) matter, which eventually cooled enough to contract and form galaxies like the Milky Way.

Once these initial galaxies formed, they began attracting one another to form groups (in our case, the Local Group) and finally galaxy clusters (such as the neighboring Virgo Cluster). This particular theory also predicts lots of small galaxies and relatively few large ones. And that's precisely what we see as we gaze into the universe.

A growing galaxy

Within a billion or so years after the Big Bang, the Milky Way had accumulated a great deal of mass. As much of it settled into the core, the galaxy's initial slow spin accelerated due to conservation of angular momentum. The spinning sphere of material quickly evolved into a disk. Subsequent generations of stars, including the Sun, formed in the disk.

But while it had become a galaxy, the Milky Way wasn't finished growing. Over time, our galaxy has grown further through the accretion of gas. Currently, much of that gas comes from the Large and Small Magellanic Clouds, the Milky Way's two largest satellite galaxies. Astronomers call this inflow, which was discovered in 1965, the Magellanic Stream.

Another source of gas for our galaxy is the Smith Cloud, discovered in 1963 by Gail P. Smith, an American student who was then studying astronomy at Leiden University in the Netherlands. This cloud of hydrogen is approximately 10,000 light-years long and 3,000 light-years wide. Astronomers originally estimated its mass at between 1 million to 2 million times that of the Sun. Current studies, however, indicate that it may have a dark matter halo up to 100 times that mass. If so, a better classification for the Smith Cloud might be a dwarf galaxy. It's heading toward the Milky Way at 200,000 mph (320,000 km/hr) and should begin to collide with the Perseus Arm of our galaxy in some 27 million years.

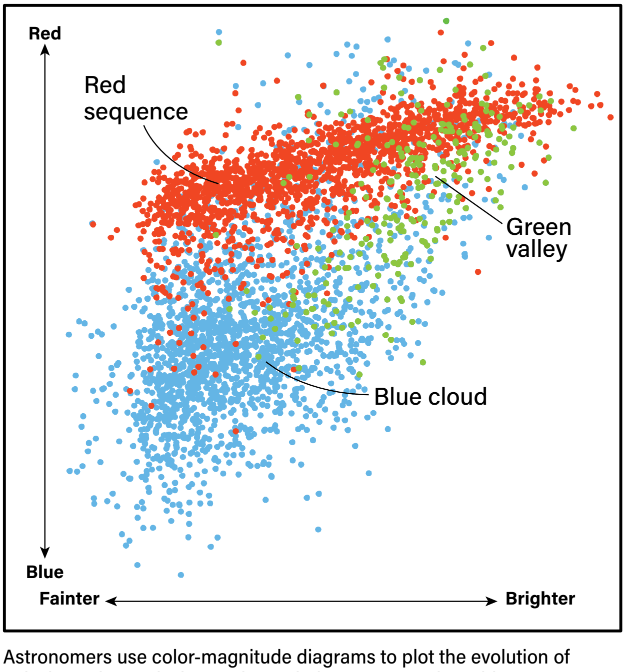
From disk to sphere

By studying large numbers of galaxies, cosmologists have concluded that there are three types. This becomes evident when placing galaxies on a color-magnitude diagram, which plots their true brightness on one axis and their mass on the other. Spiral or disk galaxies — which are blue with the light of young, hot stars — fall into a region of the diagram called the blue cloud.

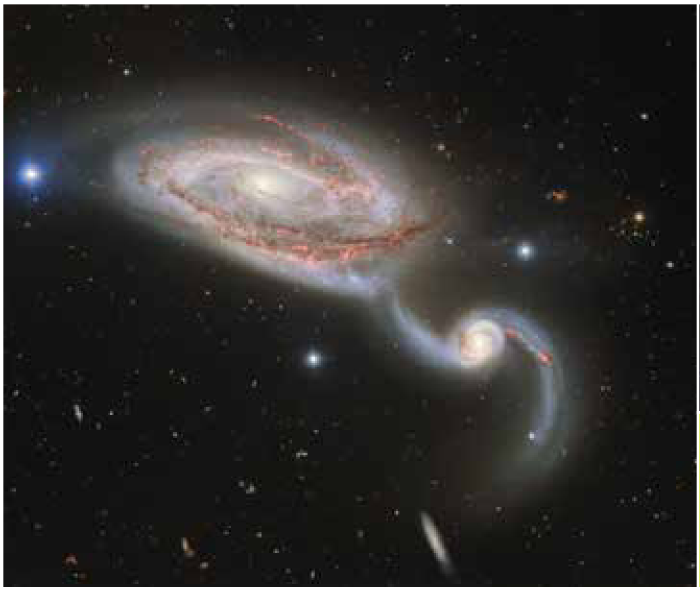
The second group, called ellipticals, consists of galaxies that are full of old, red stars. These make up a region of the diagram called the red sequence. Some elliptical galaxies are the largest objects in the universe. Their stars orbit the center randomly and are not rotating together like the ones in disk galaxies.

Astronomers now think that disk galaxies formed first, then evolved into elliptical galaxies through galaxy mergers that destroyed their flat structure. Researchers can point to many examples of merging galaxies, most of which involve two spirals that are gravitationally

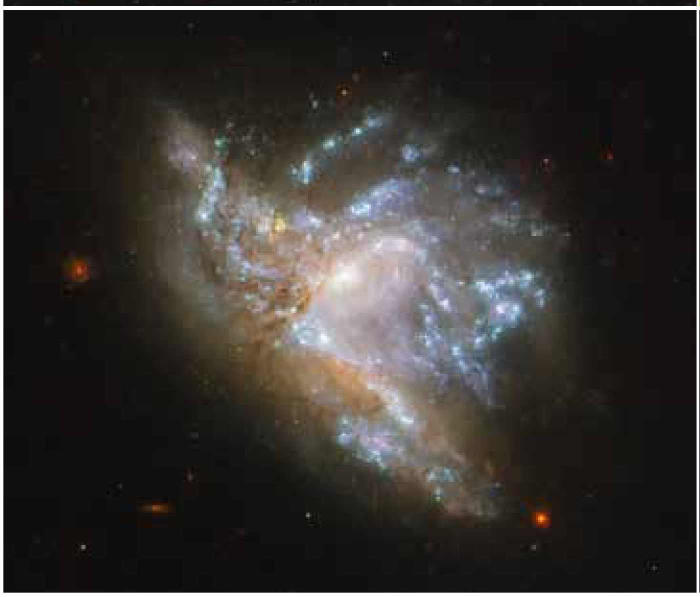
GALACTIC GERONTOLOGY



Astronomers use color-magnitude diagrams to plot the evolution of galaxies. When galaxies are born, their young stars burn blue. But as galaxies age and grow through mergers, they transition into the green valley before joining the red sequence. *ASTRONOMY*: ROEN KELLY, AFTER GAVAZZI ET AL. 2010



These examples of interacting galaxy pairs — clockwise from upper left, NGC 5394/5, NGC 2623, NGC 3921, and NGC 6052 — show how the process of merging destroys their spiral structures. CLOCKWISE FROM UPPER LEFT: INTERNATIONAL GEMINI OBSERVATORY/NOIRLAB/NSF/AURA; ESA/HUBBLE & NASA; ESA/HUBBLE & NASA; ESA/HUBBLE & NASA, A. ADAMO ET AL.



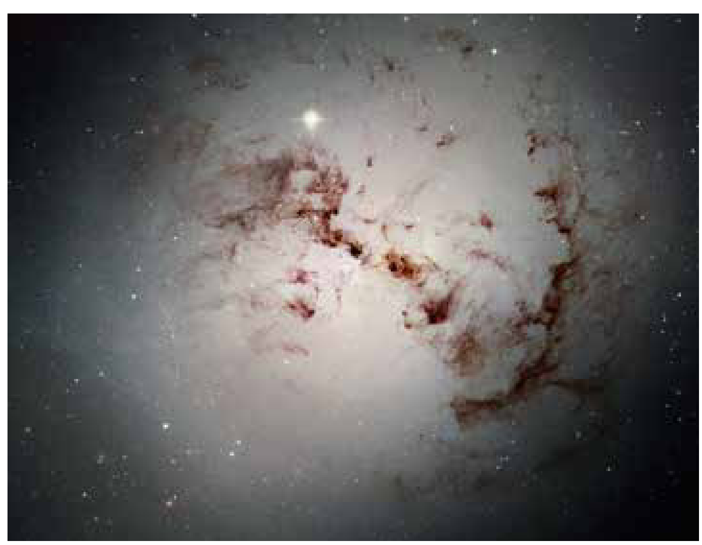
bound, and perhaps have been since their formation. If both galaxies have nearly the same mass, the single galaxy formed once the merger is complete won't look like either of them — it will be an elliptical galaxy.

Between the blue cloud and the red sequence lies the green valley — a region where blue cloud galaxies are aging into red sequence galaxies. The Milky Way sits within the green valley, although it is somewhat of an oddball; measurements of other galaxies similar to ours suggest it is among the reddest and brightest spiral galaxies that are still forming new stars.

But the Milky Way and other members of the green valley are running out of gas. Computer simulations show that all star formation in the Milky Way will stop in about 5 billion years. That's accounting for the increase in star formation when the Milky Way and the Andromeda Galaxy collide around that time. The product of this merger will likely be a giant, red elliptical galaxy.

Thus, some 19 billion years after the Big Bang, the Milky Way will begin its slow but inexorable decline — and, a trillion years from now, the end will come as its last star fades from visibility.

Michael E. Bakich *is a contributing editor of* Astronomy.



The end result of galactic mergers is a giant elliptical galaxy, like NGC 1316 in the constellation Fornax. Its dust lanes are residual evidence of the gas-rich galaxies that created it. NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STSCI/AURA); ACKNOWLEDGMENT: P. GOUDFROOIJ (STSCI)

SKY THIS MONTH

Visible to the naked eye
Visible with binoculars
Visible with a telescope

THE SOLAR SYSTEM'S CHANGING LANDSCAPE AS IT APPEARS IN EARTH'S SKY.
BY MARTIN RATCLIFFE AND ALISTER LING

A 19-hour-old Moon floats low over Turin, Italy, on February 22, 2012. You'll have the chance to catch a similar sight this month. STEFANO DE ROSA

JANUARY 2021
Twilight observing time

Following the spectacular conjunction of Jupiter and Saturn on December 21, the pair of planets continues to separate slowly night by night. In early January, we get the added benefit of Mercury, producing a fascinating trio of planets visible in the southwest 30 minutes after sunset.

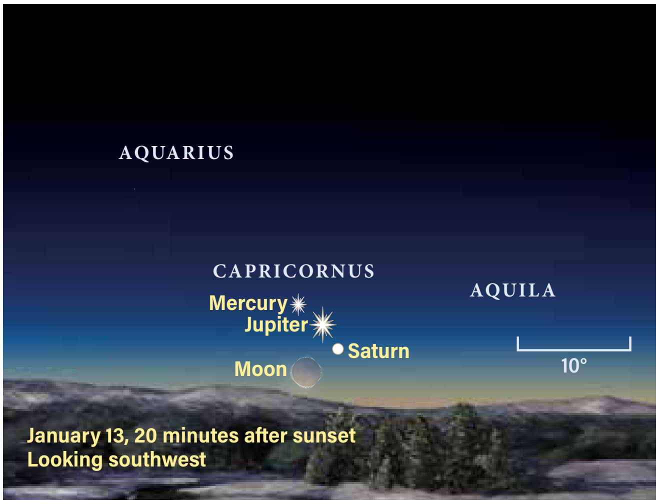
During the first week of the new year, **Jupiter** and **Saturn** start out 1.3° apart and extend to 2° by January 7, when magnitude –0.9 Mercury joins the twilight scene 3.7° below magnitude 0.6 Saturn. Jupiter shines brightest at magnitude –2.

Mercury slides up to 1.9° due south of Saturn January 9, and the next evening forms a nice equilateral triangle with the gas giants. All three planets lie within a 2.3°-wide circle.

On January 11, Mercury moves next to Jupiter and stands 1.4° to its south (lower right). Catch these events 30 minutes after sunset and for about the next 30 minutes before the last of the three planets sets around 6 P.M. local time.

There's a challenging young Moon in this region January 13 — attempts to view it will require a very clear southwestern horizon. New Moon occurs at 12 A.M. EST on January 13, and that evening at sunset will show a less-than-1-percent-lit crescent. Search for it between 20 and

The planets guard a young Moon



A trio of planets accompany a very young Moon on January 13, shortly after sunset. Look for them low in the southwest, but be aware that ideal conditions are needed to spot our satellite. ALL ILLUSTRATIONS: *ASTRONOMY*: ROEN KELLY

OBSERVING HIGHLIGHT

URANUS stands 1.7° south of **MARS** on January 21. The Red Planet is easily visible to the naked eye; binoculars or a telescope will reveal both.

25 minutes after sunset, when our satellite stands about 1° above the horizon. It's a very difficult observation unless conditions are perfect.

Look for Saturn as well, 3.7° north of the Moon and dimly glowing against bright twilight. If you spot brighter Jupiter first, use it as a guide for Saturn. The ringed planet lies 2.7° to the lower right (due west) of Jupiter. Mercury, still bright at magnitude –0.9, lies 3.3° to the upper left of Jupiter. If you spot Mercury, center it in binoculars and move about 6.5° down to find the setting Moon; but don't linger, as the Moon sets about 35 minutes after the Sun.

The Moon and Mercury form an elegant pairing on January 14, standing about 7° apart. Saturn is quickly lost in the sunset glow and heads for its January 23 conjunction with the Sun. Jupiter also slides away, now 4.6° to the lower right of Mercury (due west). Mercury continues to climb higher in the sky until January 23, when it reaches greatest eastern elongation — the second best of the year for Northern Hemisphere observers (there's a better one in May). On the 23rd, Mercury sets an hour and a half after the Sun and is a bright magnitude –0.6.

Follow Mercury through

— Continued on page 38

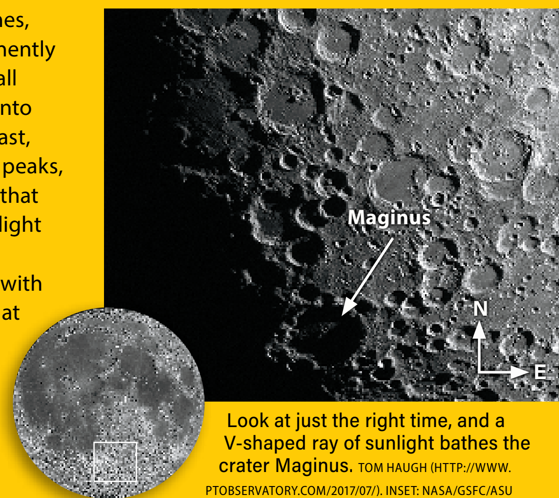
RISING MOON | The Maginus ray

THERE IS A RAY OF HOPE (okay, sunshine) on the 21st, spreading across the floor of the large, battered crater Maginus. Rilles, domes, and scarps — like the Straight Wall prominently visible a few large craters to the north — all depend on their height to cast shadows onto the surrounding plains. In complete contrast, Maginus sports a bulged-up floor, central peaks, and, most crucially, a severely dented rim that allows a prominent V-shaped splay of sunlight to thrust out across the darkness.

Don't confuse this use of the word ray with the much more common ejecta rays seen at Full Moon. The latter are the result of large impacts spreading lighter-hued material across the face of the Moon in long lines, the most spectacular of which is from nearby Tycho.

Like so much in astronomy, timing is everything. One evening earlier, Maginus is in complete darkness; one later, the Sun has risen high enough to illuminate almost all of the crater. Maginus will also appear much closer to the limb than on our map. Luna is below the ecliptic, so we are slightly looking down on it instead of being face-on. This tilting is called libration.

Maginus

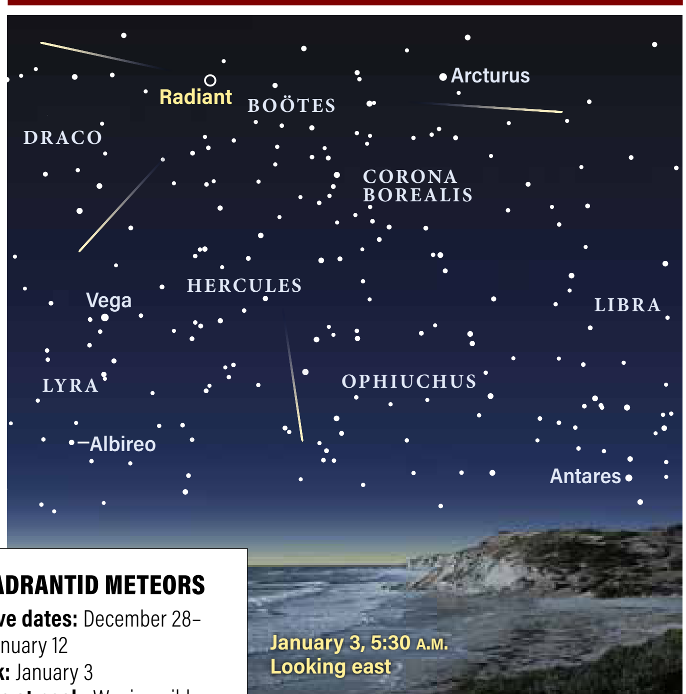


Look at just the right time, and a V-shaped ray of sunlight bathes the crater Maginus. TOM HAUGH (HTTP://WWW.PTOBSERVATORY.COM/2017/07/). INSET: NASA/GSFC/ASU

One week later, we reach Full phase. At that time, the Sun will be high overhead in the lunar sky, the previously visible shadows have disappeared, and all that remains of Maginus are subtle traces to be followed by the patient selenophile.

METEOR WATCH | Shower by moonlight

Quadrantid meteor shower



The Quadrantids' radiant, named after the defunct constellation Quadrans Muralis, rises after midnight and is highest at dawn.

QUADRANTID METEORS

Active dates: December 28–January 12
Peak: January 3
Moon at peak: Waning gibbous
Maximum rate at peak: 120 meteors/hour

THE QUADRANTID meteor shower is affected by moonlight this year. It's active between December 28 and January 12, peaking on January 3 around 9:30 A.M. EST, making that morning the best time for North American observers. Unfortunately, a bright gibbous Moon is also in the sky starting around 10 P.M. on January 2, affecting the visibility of most meteors except the brightest.

The radiant lies in Boötes and rises after midnight, and expected observable rates increase as dawn approaches. Such a strong shower should still put on an occasional show worth viewing for those willing to weather the cold temperatures of a winter's night under the stars. The Quadrantid meteors are associated with periodic comet 96P/Machholz and the minor planet 2003 EH_1.

STAR DOME

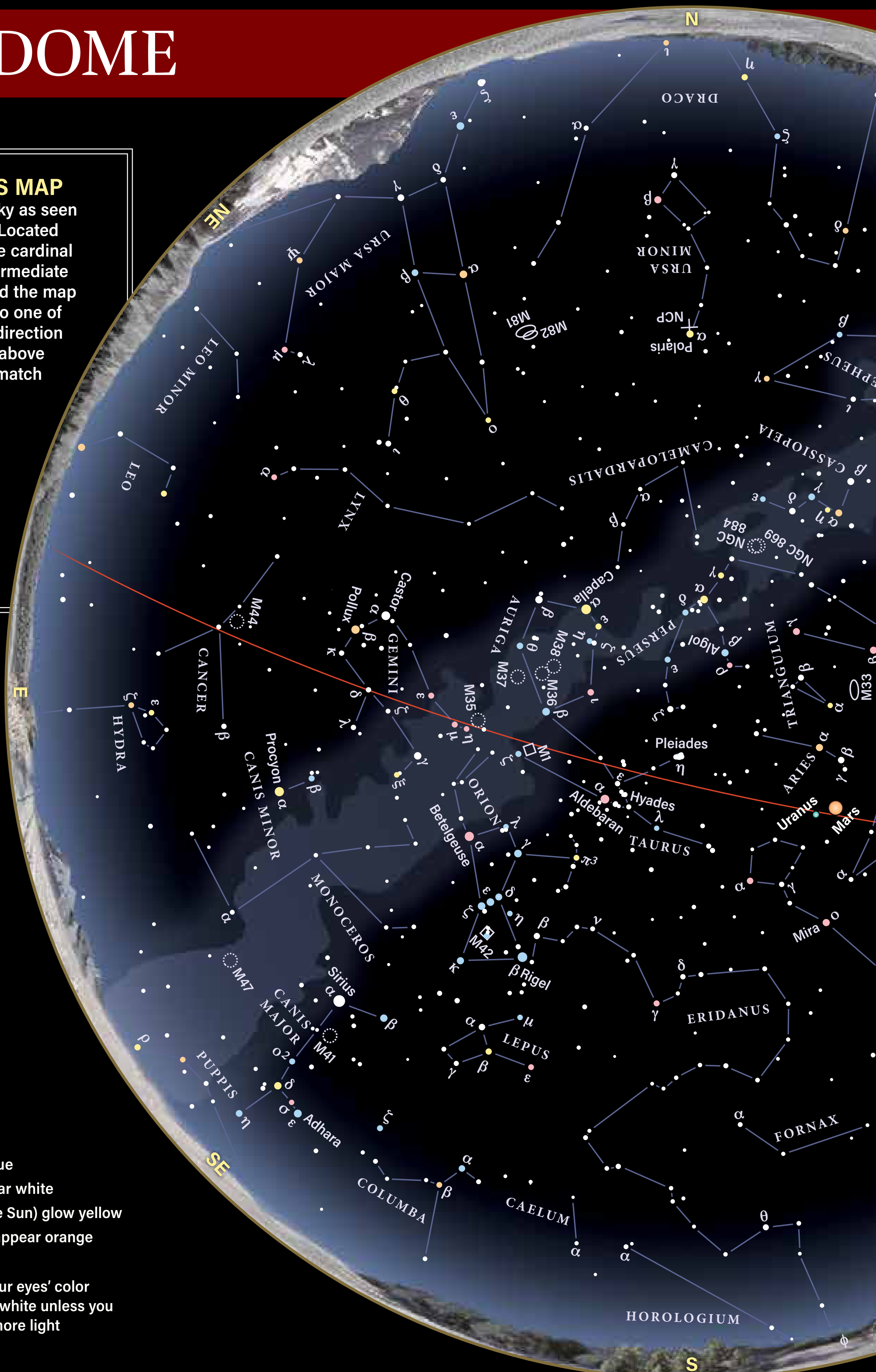
HOW TO USE THIS MAP

This map portrays the sky as seen near 35° north latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

9 P.M. January 1
8 P.M. January 15
7 P.M. January 31

Planets are shown at midmonth



MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

STAR MAGNITUDES

- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**

JANUARY 2021

SUN.	MON.	TUES.	WED.	THURS.	FRI.	SAT.
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

2 Earth is at perihelion (91.4 million miles from the Sun), 9 A.M. EST

3 Quadrantid meteor shower peaks

6 Last Quarter Moon occurs at 4:37 A.M. EST

9 The Moon is at perigee (228,284 miles from Earth), 10:37 A.M. EST

11 Mercury passes 1.5° south of Jupiter, 6 A.M. EST
The Moon passes 1.5° south of Venus, 3 P.M. EST

13 New Moon occurs at 12:00 A.M. EST
The Moon passes 3° south of Jupiter, 8 P.M. EST

14 The Moon passes 2° south of Mercury, 3 A.M. EST
Uranus is stationary, 9 A.M. EST
Pluto is in conjunction with the Sun, 9 A.M. EST

17 The Moon passes 4° south of Neptune, 1 A.M. EST

20 First Quarter Moon occurs at 4:02 P.M. EST

21 The Moon passes 5° south of Mars, 1 A.M. EST
The Moon passes 3° south of Uranus, 1 A.M. EST
The Moon is at apogee (251,258 miles from Earth), 8:11 A.M. EST
Asteroid Eunomia is at opposition, 2 P.M. EST
Mars passes 1.7° north of Uranus, 7 P.M. EST

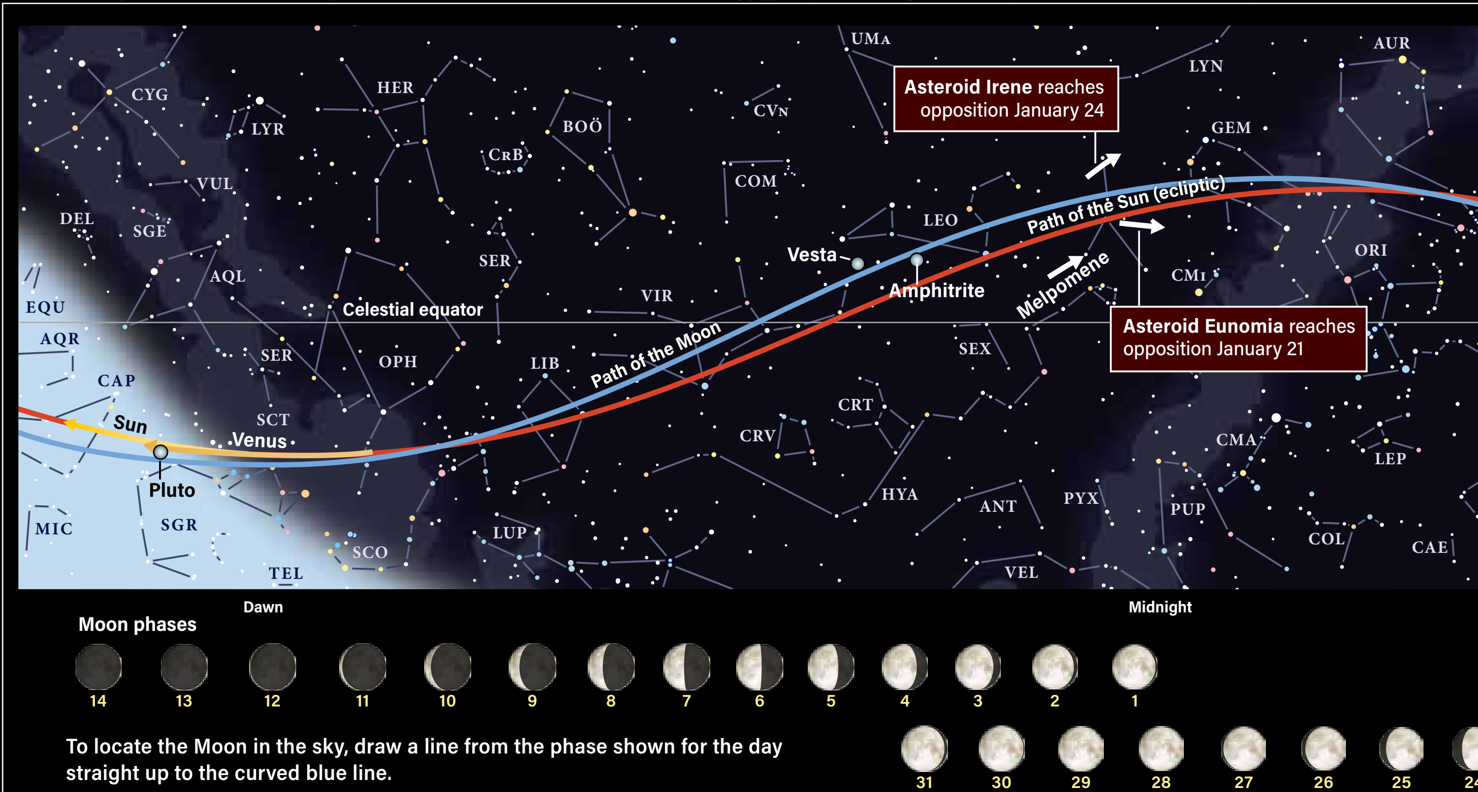
23 Asteroid Vesta is stationary, 5 P.M. EST
Mercury is at greatest eastern elongation (19°), 9 P.M. EST
Saturn is in conjunction with the Sun, 10 P.M. EST

24 Asteroid Irene is at opposition, noon EST

28 Full Moon occurs at 2:16 P.M. EST
Jupiter is in conjunction with the Sun, 9 P.M. EST

29 Mercury is stationary, 9 P.M. EST

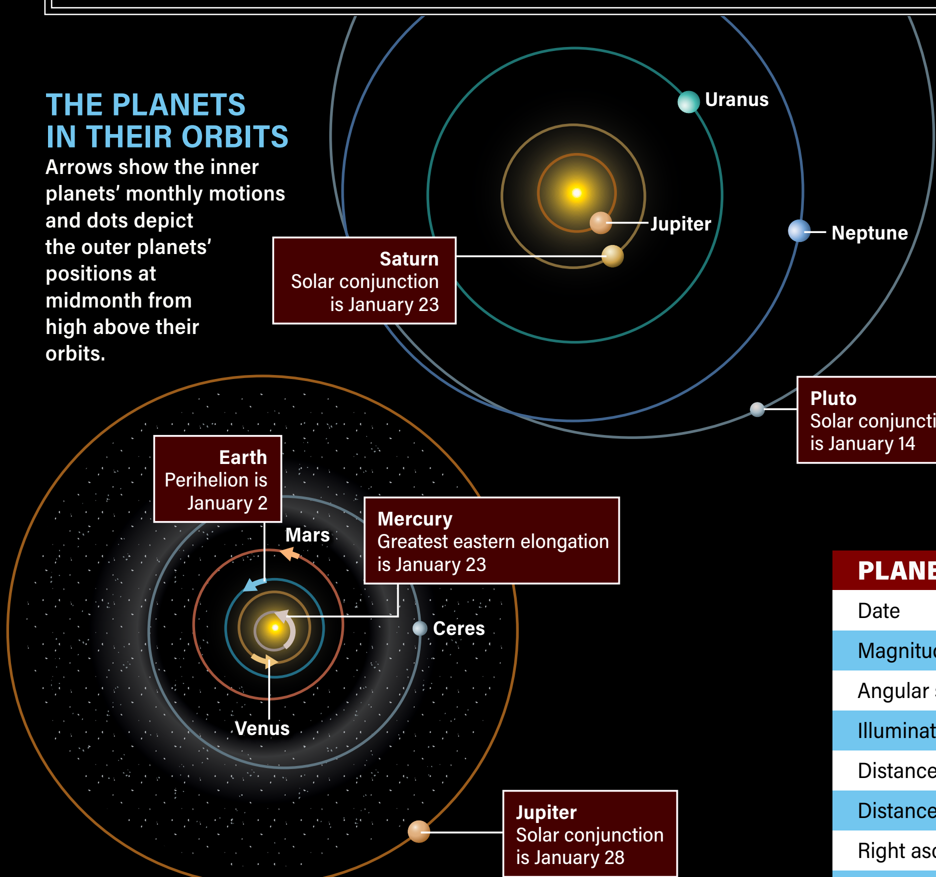
PATHS OF THE PLANETS



To locate the Moon in the sky, draw a line from the phase shown for the day straight up to the curved blue line.

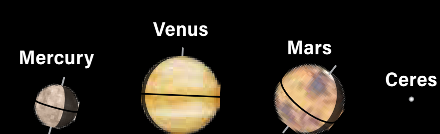
THE PLANETS IN THEIR ORBITS

Arrows show the inner planets' monthly motions and dots depict the outer planets' positions at midmonth from high above their orbits.



THE PLANETS IN THE SKY

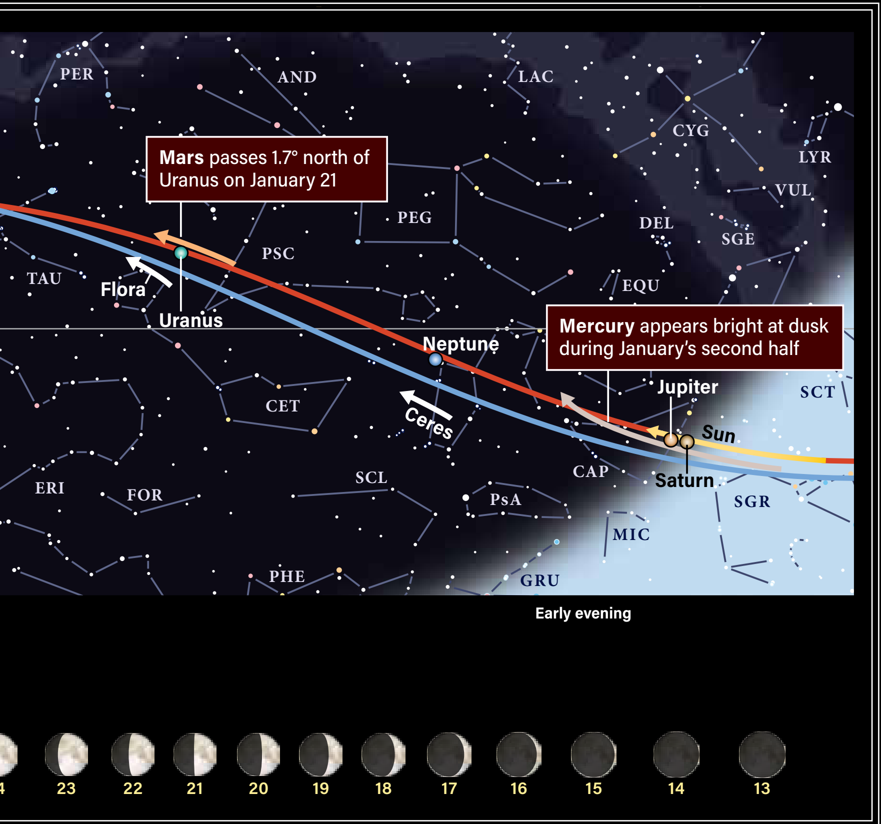
These illustrations show the size, phase, and orientation of each planet and the two brightest dwarf planets at 0h UT for the dates in the data table at bottom. South is at the top to match the view through a telescope.



PLANETS	MERCURY	VENUS
Date	Jan. 15	Jan. 15
Magnitude	–0.9	–3.9
Angular size	5.7"	10.4"
Illumination	84%	96%
Distance (AU) from Earth	1.190	1.606
Distance (AU) from Sun	0.358	0.726
Right ascension (2000.0)	20h52.5m	18h33.4m
Declination (2000.0)	–19°15'	–23°09'

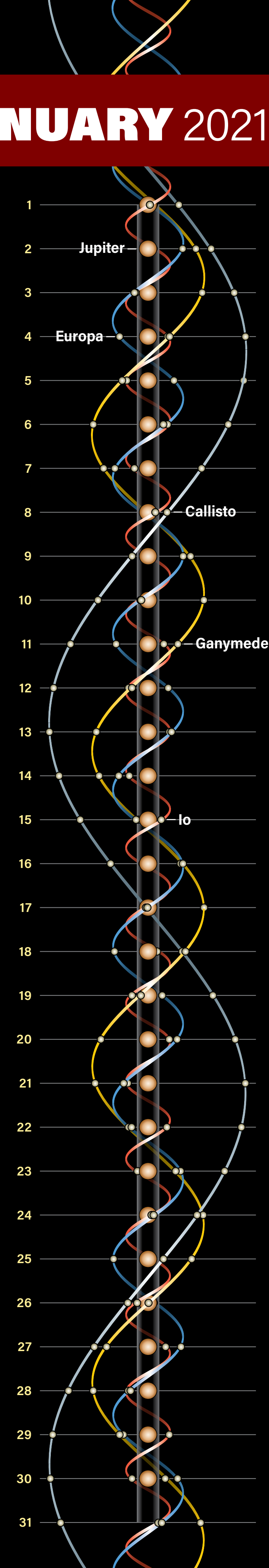
This map unfolds the entire night sky from sunset (at right) until sunrise (at left). Arrows and colored dots show motions and locations of solar system objects during the month.

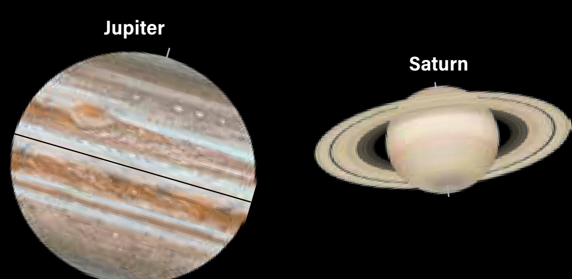
JANUARY 2021

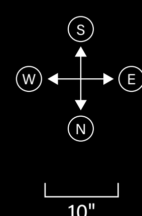


JUPITER'S MOONS

Dots display positions of Galilean satellites at 7 P.M. EST on the date shown. South is at the top to match the view through a telescope.



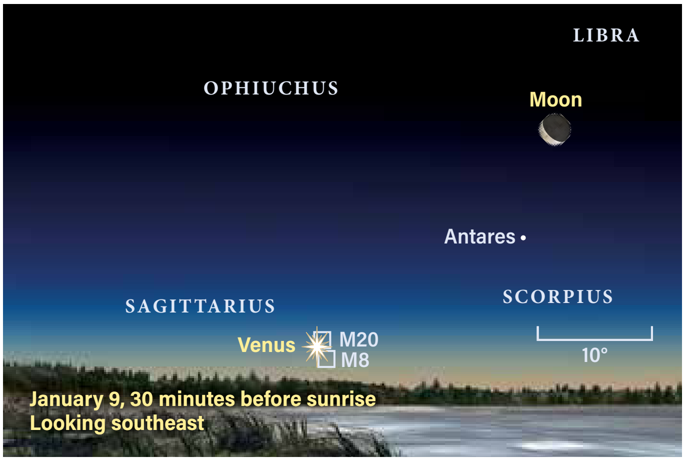




MARS	CERES	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
Jan. 15	Jan. 15	Jan. 15	Jan. 15	Jan. 15	Jan. 15	Jan. 15
0.1	9.3	–1.9	0.5	5.8	7.8	15.1
9.1"	0.4"	32.6"	15.2"	3.6"	2.2"	0.1"
89%	98%	100%	100%	100%	100%	100%
1.028	3.456	6.053	10.957	19.548	30.498	35.184
1.528	2.954	5.091	9.985	19.770	29.927	34.201
2h03.7m	23h23.4m	20h33.0m	20h21.4m	2h17.0m	23h19.4m	19h46.0m
13°44'	–13°35'	–19°19'	–19°53'	13°15'	–5°32'	–22°26'

 — *Continued from page 33*

Sandwiched by stars



Venus sits between M20 and M8 the morning of January 9. Although only the planet is visible to the naked eye, the star cluster within each nebula will appear in binoculars or a telescope.

a telescope. When it first appears in the evening sky, it's almost full (98 percent lit) and spans a mere 5". By January 14, its gibbous phase (84 percent lit) is obvious, and by January 23, it's down to 56 percent lit and has swelled to 7" in diameter. A day later, it's almost exactly half phase; it eventually slims down to 19 percent lit on the 31st, when it sets just over an hour after the Sun and has faded to nearly magnitude 1.

Neptune is an easy binocular object for the first few hours of January evenings, shining at magnitude 7.8 in eastern Aquarius. On January 1, it is 1° east of Phi (ϕ) Aquarii, a 4th-magnitude star 21° due south of Markab in the Square of Pegasus.

A quick peek at Phi reveals a pair of 6th-magnitude stars forming a triangle with Phi 1.5° to its east and northeast (96 Aquarii). Neptune spends the first three weeks of the month within this triangle. From January 17 through the 23rd, Neptune's eastward motion from night to night places it midway between these two 6th-magnitude stars, allowing easy identification in 7x50 binoculars. The planet sets by 11 P.M. local time January 1 and before 9 P.M. January 31, so catch it in the first couple of hours after sunset for the best views.

Telescopically, Neptune has little to show but exhibits a beautiful 2"-wide disk with a subtle bluish hue. The farthest planet from the Sun, Neptune's light currently takes more than four hours to reach us. Knowing this tiny object is a planet nearly four times the size of Earth makes it worthwhile to contemplate. Neptune is also a popular target for experienced amateurs using video capture — seeing conditions must be excellent to detect any features, but for those with 14-inch telescopes and larger, modern imaging brings the ice giant within range.

Mars still a great object to observe throughout January. Starting the month with an apparent size of 10" and a magnitude of –0.3, it is best viewed with scopes larger than 8 inches. Smaller scopes can achieve good results using a

WHEN TO VIEW THE PLANETS

EVENING SKY
Mercury (southwest)
Mars (south)
Jupiter (west)
Saturn (west)
Uranus (south)
Neptune (southwest)

MIDNIGHT
Mars (west)
Uranus (west)

MORNING SKY
Venus (southeast)

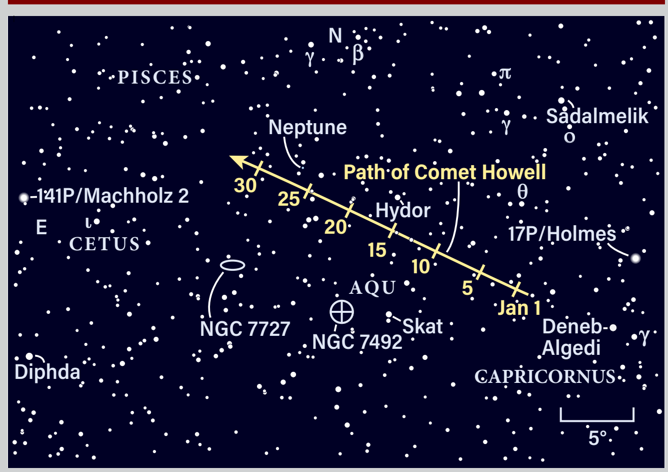
91.4 Earth reaches perihelion January 2, when our planet will stand nearly 91.4 million miles from the Sun.

COMET SEARCH | Fading slowly

FOR MONTHS after opposition, Comet 88P/Howell runs eastward against the stars. But Earth's relentless faster pace leaves it slowly fading in the distance, sinking toward the Sun. Sliding through Aquarius toward Neptune, Howell is an early evening object this month. You'll want to start looking for it 90 minutes after sunset. A 6-inch scope under dark skies will just catch its feeble 11th- to 12th-magnitude glow. Unfortunately, the Moon will be nearly Full when Howell drifts past Neptune at month's end.

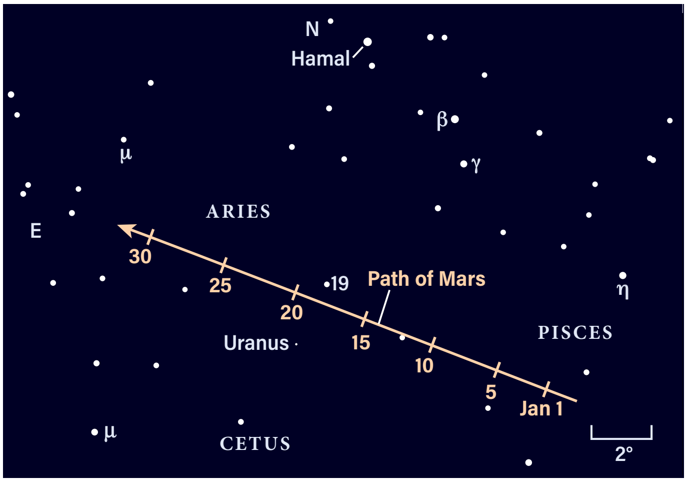
Two faint comets could burst onto the scene and outshine Howell this month. Comet 141P/Machholz 2 fragmented in 1999, but pieces keep returning and flaring up unpredictably to brighter than 10th magnitude. It travels from near Neptune across to Mira (Omicron [o] Ceti). Comet 17P/Holmes jumped to 2nd magnitude back in 2007. It's currently sliding a few degrees west and north of Howell. Observers near or south of the equator may find Comet C/2019 N1 (ATLAS) just outglowing the rest as it slides south past Alpha Centauri.

Comet 88P/Howell



Howell's inclination of about 4° means it sticks close to the ecliptic and fades slowly. By contrast, comets with steeply angled orbits brighten and disappear quickly. The location of Neptune, as well as comets 141P/Machholz 2 and 17P/Holmes, are shown on January 15.

Red beacon



You can use bright Mars as a signpost to find Uranus all month. Although Uranus moves slightly during January, its position remains within 4' of the location shown here.

planetary video camera and a quality barlow lens.

Mars starts the year within the faint line of stars representing one of the Fish in Pisces. The Red Planet crosses into Aries January 5 and makes its way across the sparse southern region of that constellation.

On the way, Mars passes apparently close to Uranus, a great time to spot that distant world. From the 18th to the 22nd, Mars and Uranus stand less than 2° apart. Uranus is exactly 1.7° due south of Mars January 21. Swing binoculars toward Mars and look for Uranus to its south, shining at magnitude 5.8. Don't confuse Uranus with a star of the same magnitude, 19 Arietis, which stands on this night due west of the Red Planet. Through a telescope, Uranus offers a bluish-green hue, a wonderful contrast to Mars' red glow.

Mars continues eastward across southern Aries through the remainder of January, fading to magnitude 0.4 as the apparent size of its disk shrinks to 8". You can continue to observe Mars past midnight; it sets one to two hours later.

Through a telescope, the Red Planet exhibits a gibbous disk 89 percent lit. Features visible early evening (9 P.M. EST) during January range from the Tharsis ridge and desert regions early in the month, to Valles Marineris midmonth, to Sinus Sabaeus and Sinus Meridiani in the third week of the month. Syrtis Major and the Hellas basin are central on the disk during January's last week.

Skipping back to **Uranus**, its general proximity to the red beacon of Mars this month makes this a perfect time to spy the distant planet, which sticks close to 19 Arietis even as Mars flies past. The ice giant's disk spans 4".

Venus rises more than an hour before the Sun on January 1, located 12° east of Antares. You'll find it low in the southeast as twilight develops. Venus is currently moving along its orbit on the far side of the Sun and shows a 94-percent-lit disk, which grows to 98 percent lit by January 31. It shines at magnitude –3.9, making it readily visible in morning twilight.

On January 9, Venus stands 4° high 45 minutes before sunrise and is located between M20 and M8, the Trifid and Lagoon nebulae, respectively. The nebulae won't be visible, but their embedded star clusters will, making for a fine view in binoculars.

Two days later, a delicate crescent Moon rises about 4° to the right of Venus on January 11. The pair closes in slightly as it rises. For another challenge, see if you can spot the bright globular cluster M22 (magnitude 5), located 46' due south of Venus the morning of January 15.

Venus drops lower in the sky each morning and becomes lost soon after the end of the month, rising only 30 minutes before sunrise

Earth reaches perihelion January 2, when we sit nearly 91.4 million miles from the Sun.

Martin Ratcliffe *is a planetarium professional and enjoys observing from Wichita, Kansas.* **Alister Ling**, *who lives in Edmonton, Alberta, is a longtime watcher of the skies.*

LOCATING ASTEROIDS

Chilling with the Bull

A GOOD SKY LOCATION can be preferable to brightness. Main-belt object 16 Psyche spends the whole month a mere 1.5° north of Aldebaran, the ruddy eye of the celestial bull.

From the suburbs, a 6-inch scope will readily pick up the 10th-magnitude dot. A 4-incher will do nicely under darker skies or for a patient city observer using high power. Thanks to the "partly cloudy" dust lanes in Taurus, Psyche won't be lost amid the populated Perseus spiral arm crossing the background. To positively identify it, make a sketch of the field and come back later to confirm which speck of light has shifted. Psyche slides only 6' in 24 hours, so there's little chance of catching its motion during a single observing session.

When Annibale de Gasparis discovered Psyche more than 50 years after 1 Ceres, it was only the 16th object found orbiting between Mars and Jupiter. Named after the Greek word for *soul*, Psyche is the target of an upcoming space mission to investigate its strange metal-rich composition.

Bull's-eye

Spend some time with Psyche, which sticks near the eye of the Bull all month. Although other asteroids are brighter, they're moving quickly through less-interesting regions of sky.

A solar flare emerges from the lower right quadrant of the Sun in this extreme ultraviolet image taken on December 19, 2014, by NASA's Solar Dynamics Observatory. NASA/SDO

OUR SOLAR SYSTEM'S ORIGIN

Researchers know how the Sun shines — but how did it form? BY MICHAEL E. BAKICH

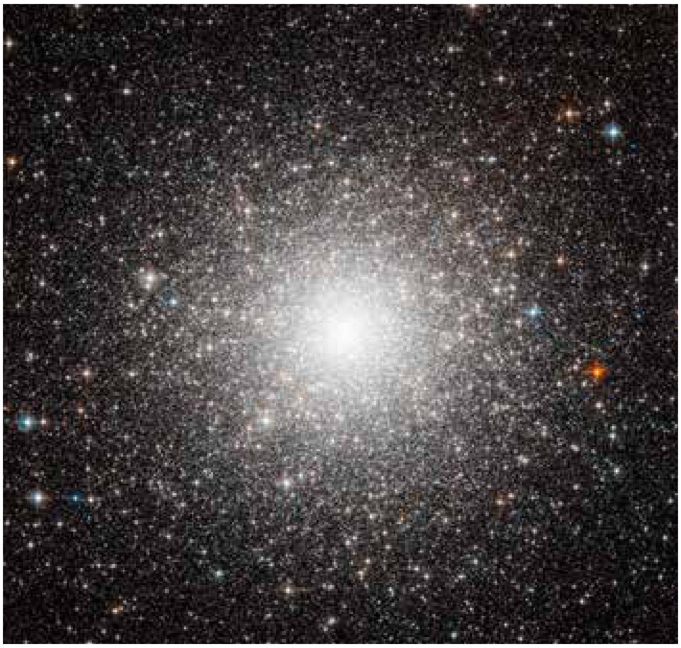
Some 4.6 billion years ago, our Sun was born from a cloud of interstellar gas and dust.

It came from a giant molecular cloud — a collection of gas up to 600 light-years in diameter with the mass of 10 million Suns — which had been circling the Milky Way for who knows how many years. The pull of gravity caused some of this cloud to collapse, until it heated up enough to emit light.

That much astronomers know. But what caused this gas cloud to collapse in the first place remains the subject of vigorous debate.

Light in the darkness

Scientists have a firm grasp on the physics of how the Sun was born. Those atoms that formed the Sun in the giant molecular cloud — mostly hydrogen and helium — were moving slowly enough that they could collide and conglomerate into clumps of matter. They then linked up with other atoms, and eventually trillions of atoms joined in. After about 10 million years, the vast majority of these concentrated



Amateur observers may have never seen Sag DEG in full, as most of it is quite spread out and faint. But they're well aware of one of its brightest components: globular cluster M54. The French comet hunter Charles Messier discovered this roughly spherical group of stars in 1778, more than 200 years before astronomers found that it is part of a larger galaxy. ESA/HUBBLE & NASA

patches grouped together at the cloud's center.

As the central mass grew, so too did the strength of gravity compacting it. This raised the pressure inside and heated it, causing it to emit infrared radiation. This clump of mainly hydrogen and helium was now a protostar — a phase that, for stars like the Sun, lasts about half a million years. The protostar continued to accrete mass as material from the cloud — which by this time had formed a disk around the central object — rained onto its surface.

As the emerging Sun packed on mass, the temperature and pressure of the protostar increased. Eventually, at a sweltering 9 million degrees Fahrenheit (5 million degrees Celsius), nuclear fusion kicked on in the protostar's core. Once this happens, most stars quickly establish a balance between the inward pull of gravity and the outward push of radiation, and the star's mass determines its final core temperature. For the Sun, that's around 27 million F, or 15 million C. At this time, the Sun truly began to shine.

But the Sun was not alone when it was born. It couldn't have been — a cloud of interstellar material that contained only the mass of one Sun wouldn't have enough gravity to begin collapsing on its own. Rather, the giant molecular clouds in which stars are born contain at least 10,000 solar masses. This leads astronomers to a simple conclusion: Our Sun formed within an open cluster of stars.

Once a cluster's stars are formed, gravitational interactions among its members usually fling some of those stars into space. Forty percent of the time, these ejected members are flying solo. The majority, however, head off as double or multiple stars. In this respect, the Sun is a bit of an oddball. (Read more about the search for stars that formed in the same nebula as the Sun in "The Sun's lost siblings," in the July 2020 issue of *Astronomy*.)

Triggering collapse

Many astronomers think the giant molecular cloud from which the Sun formed drifted through space for perhaps billions of years, only beginning to collapse when the shock wave from a relatively nearby supernova reached it. The interaction would have been gentle, though, because the exploding star was probably light-years away, and the shock wave would have dissipated as it moved through the intervening gas between the stars. But it still would have been enough to perturb the nebula — moving atoms around within it and creating regions where the density was high enough to collapse in on itself.

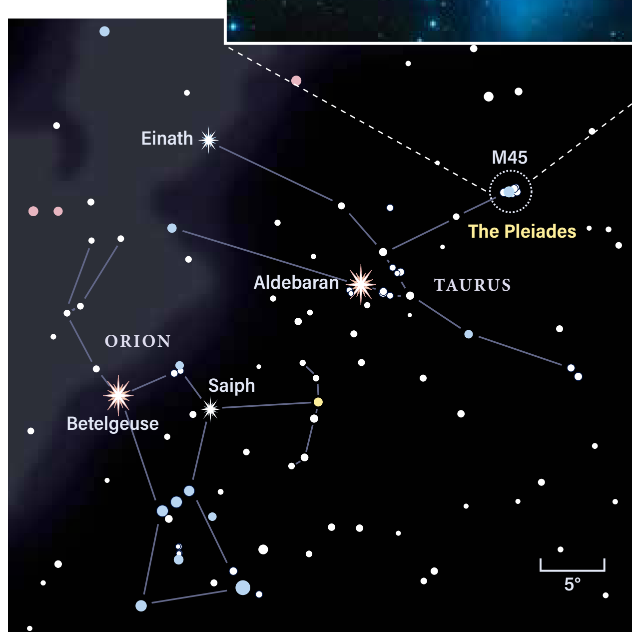
But astronomers have also proposed other possibilities.

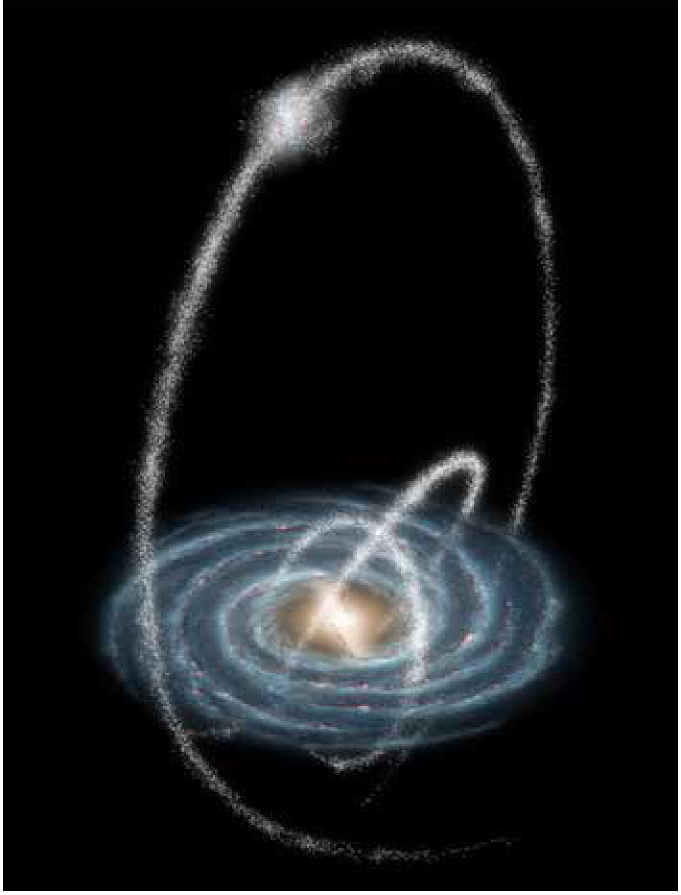
A group of researchers led by Tomás Ruiz-Lara at the Astrophysics Institute of the Canary Islands in Spain contends that the Sagittarius Dwarf Elliptical Galaxy (Sag DEG) may have provided the initial gravitational push our solar system needed to begin its life. Currently located some 70,000 light-years away and measuring about 10,000 light-years in diameter, Sag DEG is one of the Milky Way's multiple satellite galaxies, and it moves in a polar orbit around our galaxy.

Using astrometric data from the European Space Agency's Gaia space telescope, the research team uncovered evidence of three major bursts of star formation in the Milky Way's history. Those episodes happened 5.7 billion, 1.9 billion, and 1 billion years ago. Each correlates to when Sag DEG made one of its closest approaches to the Milky Way, coming within about 26,000 light-years.

The most interesting near pass was the one 5.7 billion years ago, just over a billion years before the birth of the Sun. Could it have been the trigger for our star's formation? Although we don't know for sure, says Ruiz-Lara, the timing works out.

The Pleiades (M45) is the brightest and closest open cluster, and is easy to see in the winter sky. Just draw a line up from Orion's Belt to the V of Taurus the Bull, and continue the line to M45. RIGHT: NASA, ESA AND AURA/CALTECH. BELOW: *ASTRONOMY*: ROEN KELLY





As dwarf galaxies swoop around the Milky Way, they can leave streams of stars in their wake, as depicted in this illustration. NASA/JPL-CALTECH/R. HURT (SSC/CALTECH)

When the hot wind of a Wolf-Rayet (WR) star slams into cooler interstellar gas, it collects the gas like a plow and forms a shell, as seen in this image of NGC 7635 — also known as the Bubble Nebula. Some researchers think these dense shells could become seeds for future star formation. The WR star is located at roughly 10 o'clock within the shell, offset from its center due to the asymmetric expansion of the bubble. NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)

Born from a bubble?

In 2017, Vikram V. Dwarkadas, an astronomer at the University of Chicago, and his colleagues published a paper that showed the solar system might have formed thanks to the stellar wind of a massive type of star called a Wolf-Rayet (WR) star.

Their evidence comes not from looking into the depths of space, but from examining meteorites that have landed on Earth. These meteorites were forged in the early solar system, and the abundances of their various isotopes — atoms of the same element with a common number of protons but a different number of neutrons — reflect the chemical composition of the material in the cloud that collapsed to form the Sun.

When the team compared the ratio of Aluminum-26 (Al-26) to Al-27 in meteorites, they found it to be some 17 times higher than the observed ratio for the Milky Way as a whole. This means that the aluminum didn't evolve slowly with the rest of our galaxy, but rather was injected into the nebula that formed the Sun.

The first obvious source for this extra aluminum would be supernovae, which produce heavy elements — including Al-26 — and spew them throughout the cosmos. However, further study revealed that the ratio of Iron-60 (Fe-60) to Fe-56 — both also released during supernovae — was 50 million times lower than the ratio found in the galaxy.

This led Dwarkadas and his colleagues to shift their suspicions to WR stars, which have stellar winds that release lots of Al-26 but no Fe-60. These are O-type stars that are near the end of their life and have ceased normal hydrogen fusion. With masses more than 25 times that of the Sun, their surface temperatures can top 54,000 F (30,000 C). At these temperatures, the pressure exerted by the star's photons is so powerful it can produce stellar winds with speeds up to 4.5 million mph (7.2 million km/h).

Once a cluster's stars are formed, gravitational interactions among its members usually fling some of them into space.

Perhaps this wind could have played a role in triggering star formation, seeding them with the excess aluminum in the process. In this scenario, the wind pushes into the surrounding material, forming a dense shell and depositing aluminum into it. With more material packed closely together, gravity causes regions in the shell to collapse and eventually form stars.

Dwarkadas and his colleagues believe one massive star could have provided enough Al-26 to account for the amount that researchers find in meteorites in our solar system. Of course, this wouldn't distribute Al-26 in just our solar system. Any of the concentrations of material in the original giant molecular cloud would form additional stellar systems, and each would be enriched in this isotope.

Spectroscopic studies have found corroborating evidence: Al-26 in star-forming regions throughout the Milky Way, including some in the constellations Vela, Cygnus, Orion, Scorpius, and Centaurus. And in a 2012 study of star-forming regions in Carina, astronomers found that supernovae alone couldn't account for the amount of Al-26 they detected. This points to the conclusion that the area was enriched by one or more WR stars — and perhaps triggered our Sun's formation in the process.

Astronomers already have a firm grasp on when and how the Sun formed and the process by which it shines. And perhaps soon, they'll decide which theory best explains the reason it started forming in the first place.

Michael E. Bakich *is a contributing editor of* Astronomy.

The Impact-Origin of Life Hypothesis suggests when early Earth was pummeled by asteroids, it led to vast hydrothermal systems that could have served as the crucibles for life.
ASTRONOMY: ROEN KELLY

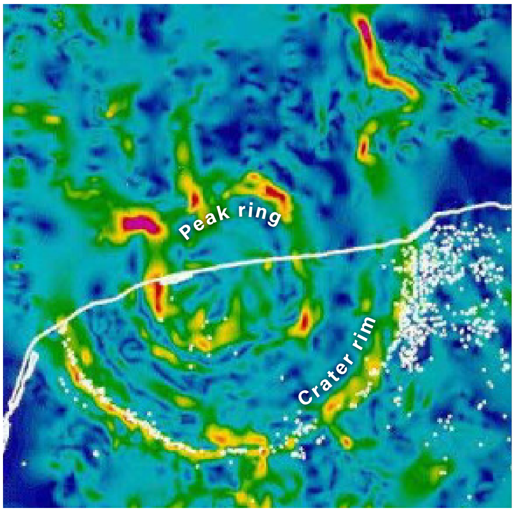
THE ORIGINS OF LIFE ON EARTH

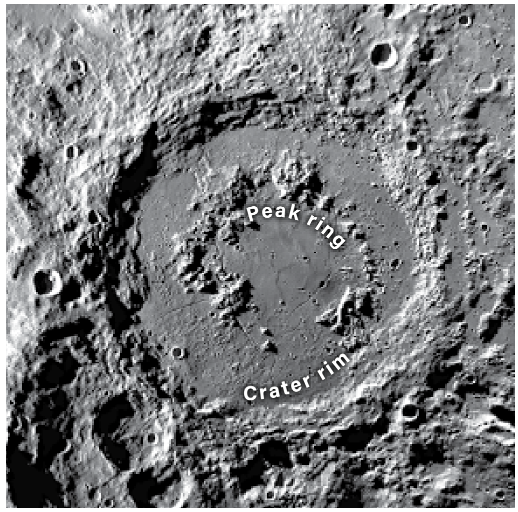
An asteroid impact may have killed the dinosaurs, but earlier cosmic strikes could have helped spawn life in the first place. **BY DAVID A. KRING**

Four billion years ago, eight burgeoning planets — including a water-rich world under fire — lurked within the debris disk around a young star. The Sun's primordial nebular gas was gone, but interplanetary space remained filled with rocky debris that pummeled planetary surfaces. The largest impacts stripped developing atmospheres and spewed melted rock into space, flinging bits of planets across the solar system.

Due to this onslaught, Earth's surface was repeatedly resculpted. The largest asteroids vaporized early seas and rock, melting the crust within each crater and creating a thick cloud of particulates that temporarily blocked sunlight from reaching Earth's surface. The molten sheets of magma, or melt sheets, created during these impacts were as deep as modern oceans, and they also heated groundwater within the nearby crust, kickstarting hydrothermal activity. This spawned enormous versions of sites like the Yellowstone volcanic caldera, churning hot water up to the surface.

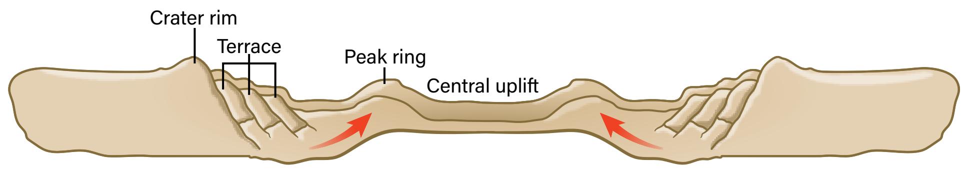
Yet, this landscape may not have been as inhospitable as it may seem. Scientists have long





This gravity anomaly map of the Chicxulub impact site (left) reveals features including sinkholes (white dots) and a peak ring structure. Schrödinger Crater on the Moon (right), also sports a prominent peak ring. LEFT: USGS. RIGHT: NASA/LRO

CRATER CROSS SECTION



When an impactor strikes a site, outward-collapsing material from the central uplift often piles up along with inward-collapsing material from the crater rim, forming a peak ring structure. *ASTRONOMY*: RICK JOHNSON

studied places like Yellowstone and other volcanic hydrothermal systems as analogues for Earth's oldest microbial ecosystems. But in recent years, researchers have examined another idea, wondering if *impact-generated* hydrothermal systems instead might hold vital clues about how life on ancient Earth first formed.

A shot at life

The Impact-Origin of Life Hypothesis suggests the bombardment Earth experienced some 4 billion years ago created vast subsurface hydrothermal systems that were ideal crucibles for prebiotic chemistry and the early evolution of life. And even if life didn't originate in those subterranean liquid conduits, the sites still would have been attractive refuges for any microbial colonies already alive when Earth's seas were vaporized by impacts.

The surface of the Hadean Earth described above has long since eroded or been swallowed by the Earth's crust. But we can still get a glimpse of this lost landscape thanks to the 66-million-year-old Chicxulub impact crater on the Yucatan Peninsula. Best known as the epicenter of the dinosaurs' hellish demise, the crater is now taking a central role for research into the origins of life.

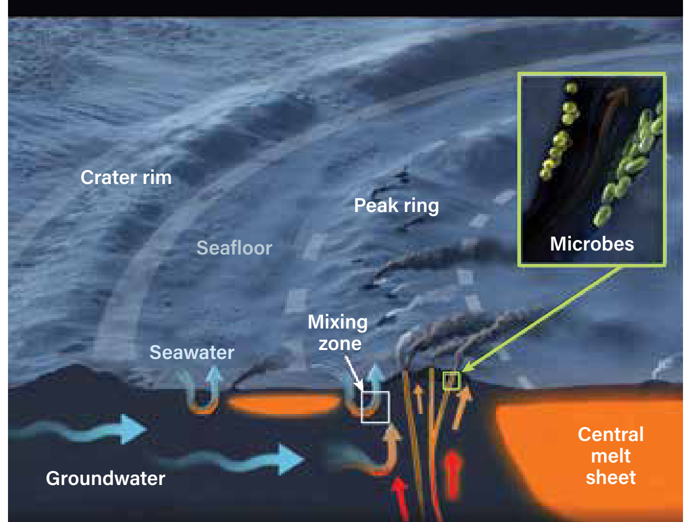
In recent years, scientists have studied Chicxulub crater by drilling deep boreholes and sending probes into the crust. These efforts have resulted in many samples of the once-dynamic impact site, revealing a post-strike cauldron of molten rock and circulating hot water.

Following the impact, Chicxulub crater's hydrothermal system was nearly 10 times larger than the Yellowstone caldera, spanning virtually the entire 112-mile-wide (180 kilometer) basin. But activity was especially intense near the peak ring inside the crater, which surrounded the central melt sheet. Groundwater flowed beneath the outskirts of the crater, taking advantage of porous, permeable rock created during the impact event. With temperatures exceeding 572 degrees Fahrenheit (300 degrees Celsius), this hot and mineral-laden water circulated up from depths as great as 3.1 miles (5 km).

Over the span of at least 2 million years, the hydrothermal system would have cooled as it aged. And eventually, the water would have reached the ideal thermal window for hosting heat-loving, or thermophilic, organisms — between about 106 F (41 C) and 252 F (122 C).

Such systems were prevalent during the impact bombardment that shaped the Hadean. Estimates of the size and frequency of impactors vary, but one model suggests our planet was resurfaced by about 6,000 impactors, each larger than the roughly 6-mile-wide (10 km) Chicxulub impactor. Those impactors may have produced some 200 impact craters 620 to 3,100 miles (1,000 to 5,000 km) in diameter, each a potential incubator for microbial life. These impact-generated hydrothermal systems may have been far more expansive (and common) than volcanic systems, like those at Yellowstone and along mid-ocean ridges today.

AN IMPACT ENVIRONMENT



The hydrothermal system beneath an impact site such as Chicxulub crater depends on groundwater flowing inward through porous rock toward a central melt sheet of magma. It then mixes with hot, mineral-rich water before bubbling up through vents in the seafloor, which are concentrated along the crater's peak ring. VICTOR O. LESHYK FOR THE LUNAR AND PLANETARY INSTITUTE

Yellowstone is a vast, geologically active region. Though it was not the result of a cosmic impact, the site's conditions are relatively similar to those found in the impact environments where many believe life first formed.
BROCKEN INAGLORY/WIKIMEDIA

The right ingredients

Having the proper temperature is only part of the recipe for cooking up life — the right ingredients in the Earth's crust are also necessary.

While today's atmosphere is mostly nitrogen and oxygen, the Hadean atmosphere may have instead been dominated by hydrogen, carbon dioxide, carbon monoxide, and ammonia, before being filled with steam and rock vapor produced by the largest impact events. As intense ultraviolet rays from the young Sun beat down on that post-impact, debris-filled atmosphere, it could have generated a hydrocarbon haze in the sky, casting a deep yellow-orange smog that eventually settled to the surface, forming hydrocarbon-rich sediment layers on top of multi-mile thick layers of impact ejecta.

Hot, mineral-rich water venting through those rubble piles of hydrocarbon-rich sediments would have been chemical factories for organic reactions, providing the necessary feed stock for microbial ecosystems. If one had an ear for hydrothermal activity following a strike, one might even hear roaring gases venting at the surface of ring-shaped island chains surrounding the centers of impact sites, with plumes of bubbling fumes and dissolved pollutants thrumming above the seafloor, and Earth itself creaking as the crater settled.

An uncertain past

The plumbing of a hydrothermal system may have shifted, too, suddenly growing silent in one area while booming in another as earthquakes caused by other impacts changed water pressures and closed vents through collapse, cutting off hydrothermal channels. Still, these fluctuations wouldn't mean all life there was snuffed out. Organisms already living in these environments would have dutifully migrated throughout Earth's crust, following the fluids that provided the necessary temperatures and nutrients to drive metabolic reactions.

Microbial ecosystems even may have eventually breached the surface and spread across the floors of impact craters. Any life that emerged would have had only a short time to thrive, however, before being decimated or extinguished entirely by the next large impact. But such was life on Earth, at least until the basin-forming impact epoch ended.

The Impact-Origin of Life Hypothesis has its rivals, but many competing ideas still rely on hydrothermal fluids.

The Impact-Origin of Life Hypothesis has its rivals, but many competing ideas still rely on hydrothermal fluids. In one such model, the spreading centers of oceanic crust produced the mineral-rich setting that was necessary for life to form. Other models envision continental hydrothermal sites, not unlike the volcanic edifices at Yellowstone. So, while each possible scenario has its own unique attributes, a complex site with heated, mineral-rich fluid is the common thread linking many of them.

At this point in time, existing evidence cannot resolve an impact origin of life from a volcanic origin of life. However, in a heavily impact-cratered Hadean world, it is important to understand that those alternative types of hydrothermal systems existed in a landscape shaped by impact basins. So, one way or another, life may have emerged from an impact crater, either from an impact-generated hydrothermal system as described here, or from a volcanic hydrothermal system that grew within one of those impact sites.

David Kring *is a planetary geologist at the Lunar and Planetary Institute who led sample analyses for the Chicxulub crater discovery team. He is also the world's foremost expert on Meteor Crater.*

LOOKING FOR LIFE IN THE UNIVERSE

Possibilities for extraterrestrial life seem limitless, but a few scientific rules can help us find it. BY MORGAN L. CABLE

The question "Are we alone?" has long permeated our collective psyche. As early as the second century A.D., humankind was recording stories of aliens and space travel: Lucian of Samosata's *A True Story* features a war between the inhabitants of the Sun and the Moon. And a simple look at ancient mythology tells us that humankind has wondered what might exist among the stars for far longer.

With modern instruments, astronomers have discovered more than 4,000 planets orbiting other stars, and many of these exoplanets are far more exotic than we could have imagined. What kind of life could exist on a world with two or three suns? Or a world made of diamond? How about one where it rains glass? The universe is a really, really big place, so the possibilities are almost endless.

Before we go too far down the rabbit hole, there are many worlds that appear Earth-like — meaning they're in a stable orbit around a G–type star and they sit in the star's habitable zone, where liquid water can exist on the planet's surface. Scientists have even found multiple ocean worlds in our own solar system, such as Jupiter's and Saturn's moons Europa and Enceladus, which both hide oceans beneath their icy shells.

Still, the universe is strange, and, as Dr. Malcolm says in *Jurassic Park*, "Life, uh, finds a way." If science has learned one thing from science fiction, it's that extraterrestrial life could be beyond even our wildest dreams. But life still has to follow some basic rules.

The TRAPPIST-1 planetary system is home to seven of the thousands of exoplanets astronomers have found orbiting other stars. NASA/JPL-CALTECH

A subsurface ocean, as salty as Earth's Dead Sea, is expected to be hiding on Titan. NASA/JPL/UNIVERSITY OF ARIZONA

The chemical necessities

Life is likely to rely on locally available building blocks for parts; scientists don't expect life to be based on an element that's extremely rare, such as iridium or platinum. When searching for life in the cosmos, astronomers tend to look for what is most probable (and detectable). That means homing in on chemical signatures containing the 10 most abundant elements in the observable universe: hydrogen, helium, oxygen, carbon, neon, iron, nitrogen, silicon, magnesium, and sulfur.

But that's not the whole story. For example, silicon is more common on Earth than carbon, and yet all life on Earth is carbon based, meaning that carbon forms the scaffolding for other elements to be built upon. While silicon is somewhat similar to carbon in terms of its elemental makeup, it is different in important ways. For instance, at Earth's temperature, carbon dioxide (CO_2) is a gas, making it easy to banish from a cell. (Mammals do it all the time.) If Earth organisms were silicon-based, however, they might have more of a problem, as silicon dioxide (SiO_2) is a solid at room temperature.

A carbon backbone also ensures chemical processes necessary for life can occur more easily. For this reason (combined with a multitude of others), life on Earth uses a subset of elements: carbon, hydrogen, nitrogen, oxygen, phosphorous, and sulfur, also known as CHNOPS.

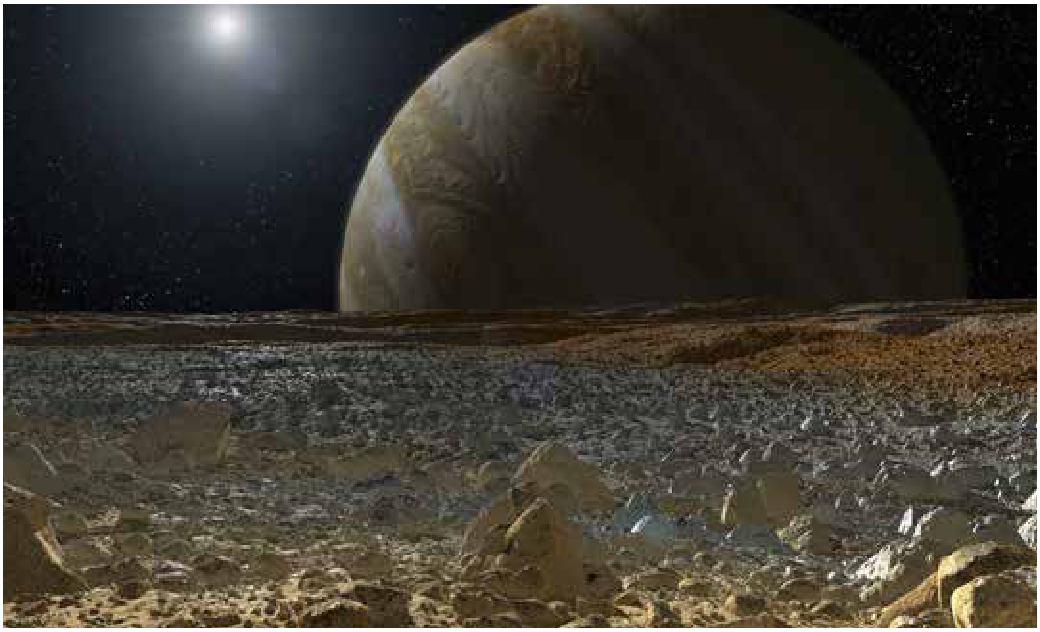
It's entirely possible that some life can break the familiar CHNOPS paradigm. Scientists are looking for examples, but they've yet to find one on Earth. So, for now, any search for extraterrestrial life is focused on CHNOPS and governed by the rules of earthly chemistry. Other physical rules observed on Earth and in the solar system can also inform our search.

Follow the water

There's another important ingredient for life: liquid. So far, all known life requires water. This makes sense — water helps move things around. It carries nutrients into cells, ferries waste away, and keeps things running smoothly. Whether life requires water for these processes is a key question in the search for life. Theoretically, any liquid could work.

Astronomers may be able to test this theory in our own cosmic backyard. Saturn's moon Titan is absolutely frigid, with an average surface temperature of –290 degrees Fahrenheit (–179 degrees Celsius). Water is frozen solid at these temperatures. But other compounds, ones that usually exist as gases on Earth, are liquids. Both methane and ethane are prevalent on Titan and form clouds, rain onto the surface, flow into rivers, and pool into giant seas at the poles. Life could be hiding there.

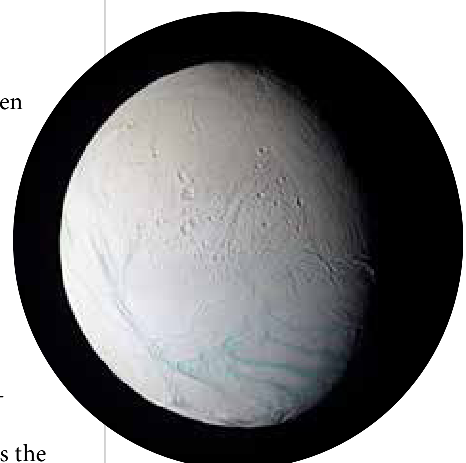
If it is, it would be very different from all life on Earth, and not just because it wouldn't use water. Liquids come in two distinct "flavors": polar and nonpolar. Water is polar, meaning the H_2O molecule has a positive end and a negative end. This is important because



This simulated view from the surface of Europa shows the potentially rugged, icy surface of the moon and the fantastic view of its host planet, Jupiter. Scientists suspect a subsurface ocean lies beneath this moon's icy crust. NASA/JPL-CALTECH

ABOVE: Beneath Callisto's heavily cratered surface lies a layer of ice about 124 miles (200 km) thick. Researchers believe a shallow ocean, just 6 miles (10 km) deep, may be directly beneath the ice of this jovian moon. NASA/JPL/DLR

BELOW: Saturn's moon Enceladus features an underground ocean at its south pole. The ocean is thought to feed its water jets; in 2015, Cassini flew through a plume and detected hydrogen, one of the necessities for life. NASA/JPL/SPACE SCIENCE INSTITUTE



water only dissolves other polar molecules — like amino acids, proteins, or DNA — allowing cells to use them effectively. In contrast, methane and ethane are both nonpolar, so molecules that dissolve well in water will not dissolve in liquid methane or ethane. Thus, the complex molecules that Earth-based life depends on, such as DNA, would not be usable by any hypothetical life on Titan.

Scientists are looking into whether these complex molecules could be substituted with something else, but they haven't found any that perform the types of chemical reactions needed for life to exist. This doesn't mean life is impossible in Titan's lakes; it just means we don't yet fully understand Titan's potentially complex chemical system.

In our own backyard

With a whole universe of planets to explore, it may seem trivial to search for life within our solar system. But, unlike exoplanets, the worlds in our backyard are within reach. The nearest exoplanet is 4.2 light-years away. Even the fastest spacecraft humanity has launched would take nearly 20,000 years to reach it. In comparison, spacecraft can reach Titan and Europa in less than 10 years.

In fact, NASA is currently working on two spacecraft to help assess the habitability of these fascinating worlds. The Europa Clipper mission will make multiple flybys of Europa, and the Dragonfly rotorcraft will explore Titan's surface and weather.

And there are even more worlds in our solar system to explore for life. The list so far includes Enceladus, Ceres, Ganymede, Callisto, Dione, Triton, and possibly even Pluto. Any one of these worlds could answer the question "Are we alone in the universe?" — albeit in a more microscopic way.

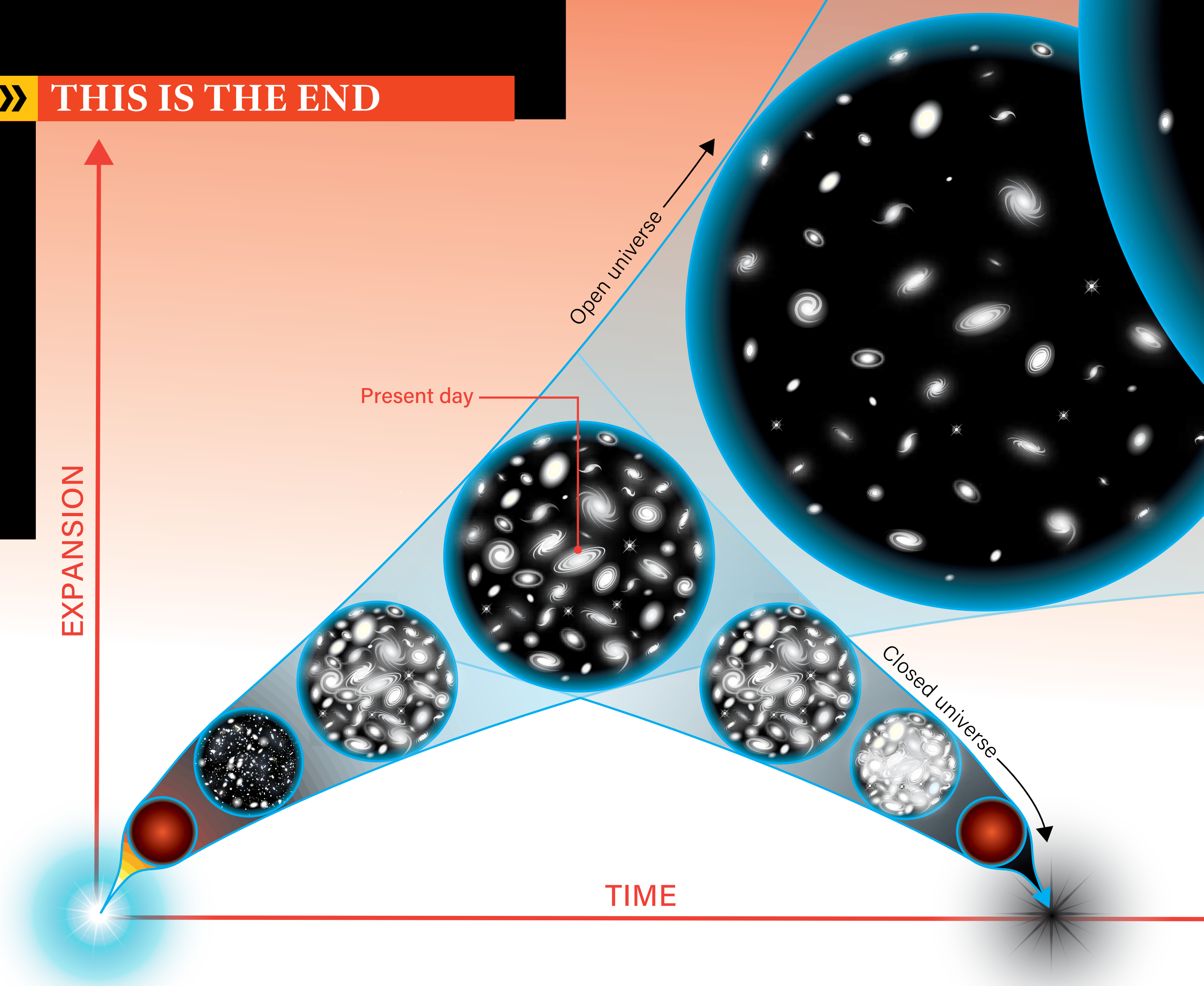
To paraphrase Carl Sagan, we stand at the shore of the cosmic ocean; recently, we have waded a little way out, and the water seems inviting. The more we search for life, the more we understand about our cosmic origins and the more questions emerge. But we have to search, because that is what makes us human: the drive to know, to learn, to discover. As Sagan so aptly puts it: "Hopefully, one day, we'll realize that we are not alone in the cosmic dark, but that our pale blue dot is just one of many life-sustaining worlds scattered throughout the cosmos."

Morgan L. Cable *is a scientist and supervisor of the Astrobiology and Ocean Worlds Group at the NASA Jet Propulsion Laboratory in Pasadena, California. Her research involves searching for life and habitability in our solar system and beyond.*

FINDING PROOF OF LIFE

JPL/NASA

When it comes to searching for habitable planets, we only have a sample size of one. We haven't even fully characterized the wild and weird places in our own cosmic backyard to understand the diverse environments life could occupy. So how do scientists plan to recognize alien life when we find it? Instead of looking for life, we look for "not not-life." An instrument designed to characterize the chemicals in an environment (for example, the surface of an exoplanet or the ocean of Enceladus) could search for anomalies in the environment, such as molecules that would only appear in the presence of life. While it seems a bit indirect, the detection of something unexpected — something that makes a scientist go, "Hm, that's weird" — may be the strongest evidence for life we might find, and it would narrow down the list of worlds to ones that are potentially habitable. From there, the list reduces to worlds we could conceivably visit. *—M.L.C.*



THE BIG CRUNCH VS.

Astronomers once thought the universe could collapse in a Big Crunch. Now most agree it will end with a Big Freeze. BY ERIC BETZ

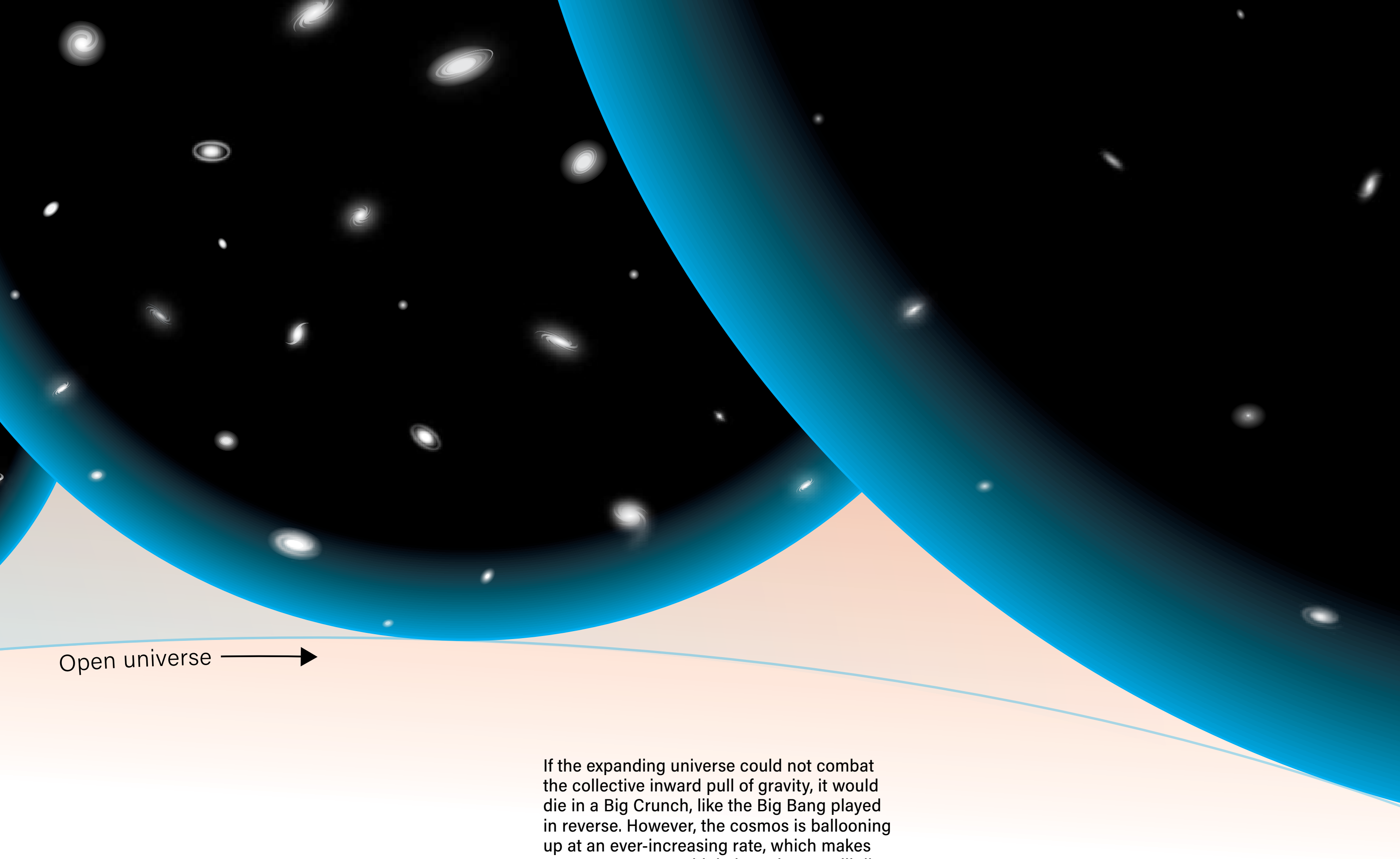
How will the universe end? Humanity has pondered this question for thousands of years. And now science actually has the knowledge and tools to attempt an answer.

Until rather recently, astronomers thought the cosmos would repeatedly expand and collapse in an infinite cycle of cosmic death and rebirth. But the best evidence points to a distant Armageddon filled with more existential dread than the Book of Revelation. Trillions of years in the future, long after Earth is destroyed, the universe will drift apart until galaxy and star formation ceases. Slowly, stars will fizzle out, turning night skies black. All lingering matter will be gobbled up by black holes until there's nothing left. Finally, the last traces of heat will disappear.

Rather than meeting its end through fire and brimstone, the cosmos will likely succumb to "heat death." Astronomers call it the Big Freeze.

Alpha and Omega

The universe didn't always seem destined to end this way. Roughly a century ago, astronomers thought that our Milky Way Galaxy was the entire universe. Our cosmos appeared static — it had always been, and would always remain, roughly



If the expanding universe could not combat the collective inward pull of gravity, it would die in a Big Crunch, like the Big Bang played in reverse. However, the cosmos is ballooning up at an ever-increasing rate, which makes most astronomers think the universe will die in a Big Freeze, where any lingering particles are separated by distances greater than the current observable universe. *ASTRONOMY:* ROEN KELLY

THE BIG FREEZE

the same. However, as Albert Einstein formulated his theories of relativity, he noticed signs of something strange. His equations implied a universe in motion, either expanding or contracting. So Einstein added a fudge factor — a cosmological constant — that held the universe in a more appealing steady state.

"Einstein was not being stupid; he was feeling the feeling of astronomers," says Nobel Prize-winning cosmologist John Mather, the head scientist for NASA's James Webb Space Telescope.

However, around the same time, astronomers began to accept that some of the fuzzy spiral-shaped nebulae they observed through their telescopes were not collections of stars in our galaxy. They were other galaxies entirely. And when Edwin Hubble meticulously measured their motions, he showed these galaxies were indeed moving away from our own. Humanity had discovered that the universe is expanding.

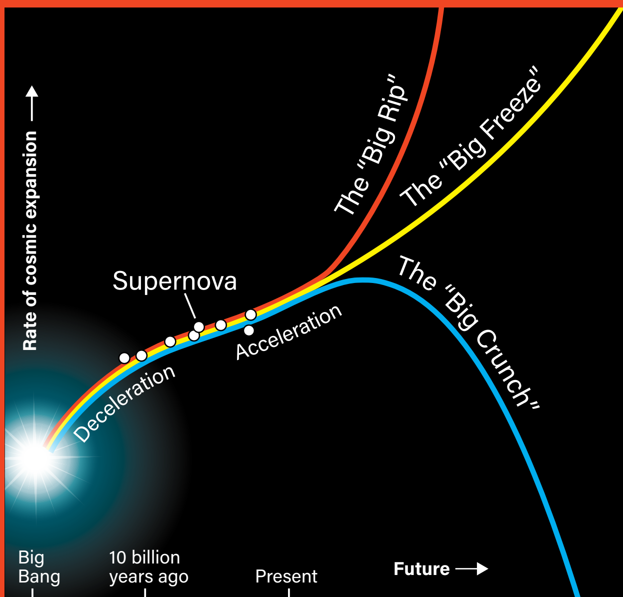
Pressing rewind on that expansion ultimately revealed that the entire universe was born in a violent Big Bang some 13.8 billion years ago. With its foundations firmly fixed, cosmology turned to the next great question: How will the universe end?

There are two main ways for an expanding universe to die: The cosmos could eventually collapse back in on itself, or it could continue inflating forever. To find out which is right, astronomers had to fast-forward the evolution of the universe.

The Big Crunch

In 1922, Russian physicist and mathematician Alexander Friedmann derived a famous set of equations aptly named

PICK YOUR COSMIC POISON



There are a few ways the universe might end, but exactly how depends on how the rate of cosmic expansion changes in the future. If gravity overpowers expansion, the cosmos will collapse in a Big Crunch. If the universe continues to expand indefinitely, as expected, we'll face a Big Freeze. But if dark energy pushes the expansion rate to near infinity, we'll have a Big Rip that tears everything, even atoms, apart. *ASTRONOMY*: ROEN KELLY

NASA's Spitzer and WISE infrared observatories paired up to reveal this view of the region around the Milky Way's supermassive black hole, Sagittarius A*. Supermassive black holes are likely to be the last reservoirs of matter in the entire universe. Yet even they will eventually evaporate. NASA/JPL-CALTECH/JUDY SCHMIDT

the Friedmann equations. These calculations showed that our universe's destiny is determined by its density, and it could either expand or contract, rather than remain in a steady state. With enough matter, gravity would eventually halt the cosmos' expansion, causing it to come crashing back inward.

In the 1960s and 1970s, when astronomers added up all the matter in the known universe, they calculated there was enough mass that the cosmos should ultimately collapse to an infinitely dense state, or perhaps even a gargantuan black hole.

Some speculated that once compressed into an infinitely small point — the Big Crunch — the universe would kickstart yet another expansion, or Big Bounce.

In the 1970s and 1980s, physicist John Wheeler, who helped coin the term *black hole*, became a leading proponent of the Big Crunch. To him, it was an obvious fate. A revolution in understanding black holes was underway, and Wheeler saw each one as an "experimental model" of the universe's final state.

But Wheeler's Big Crunch fondness was partially born from aesthetics, he admitted. It was easy to picture.

The Big Freeze

Unfortunately, reality is not always so relatable.

"Just because we might find a cold, empty universe an unappealing future doesn't mean that that's not where things are headed," Columbia University physicist Peter Woit writes on his blog, *Not Even Wrong*.

In the late 1990s, two separate groups of scientists were surveying the distant universe, studying dying stars called type Ia supernovae, which serve as standard candles that help establish cosmic distances. They found distant blasts appeared dimmer, and were therefore farther away, than expected. The universe's expansion wasn't slowing down at all — it was speeding up. The teams had independently stumbled onto dark energy, shattering existing models of the universe. (See "The mystery of dark energy," page 53.)

The expectation-defying discovery of dark energy showed the universe was very unlikely to collapse in a Big Crunch. Even with all the matter in the universe tugging inward, gravity will never be strong enough to overcome the inflating effect of dark energy. In other words, the ballooning universe is destined for a Big Freeze.

These days, astronomers think normal matter comprises just 5 percent of the universe's contents. Meanwhile, dark matter makes up some 26 percent, and dark energy accounts for the final 69 percent. Dark energy, it turns out, seems to be the real-world force behind Einstein's cosmological constant, which plays a major role in preventing a Big Crunch-style collapse.

Thanks to the expansion caused by dark energy, within a couple of trillion years, all but the closest galaxies will be too far away to see. Then, perhaps 100 trillion years later, star formation will cease, as dense stellar remnants like white dwarfs and black holes lock up any remaining material.

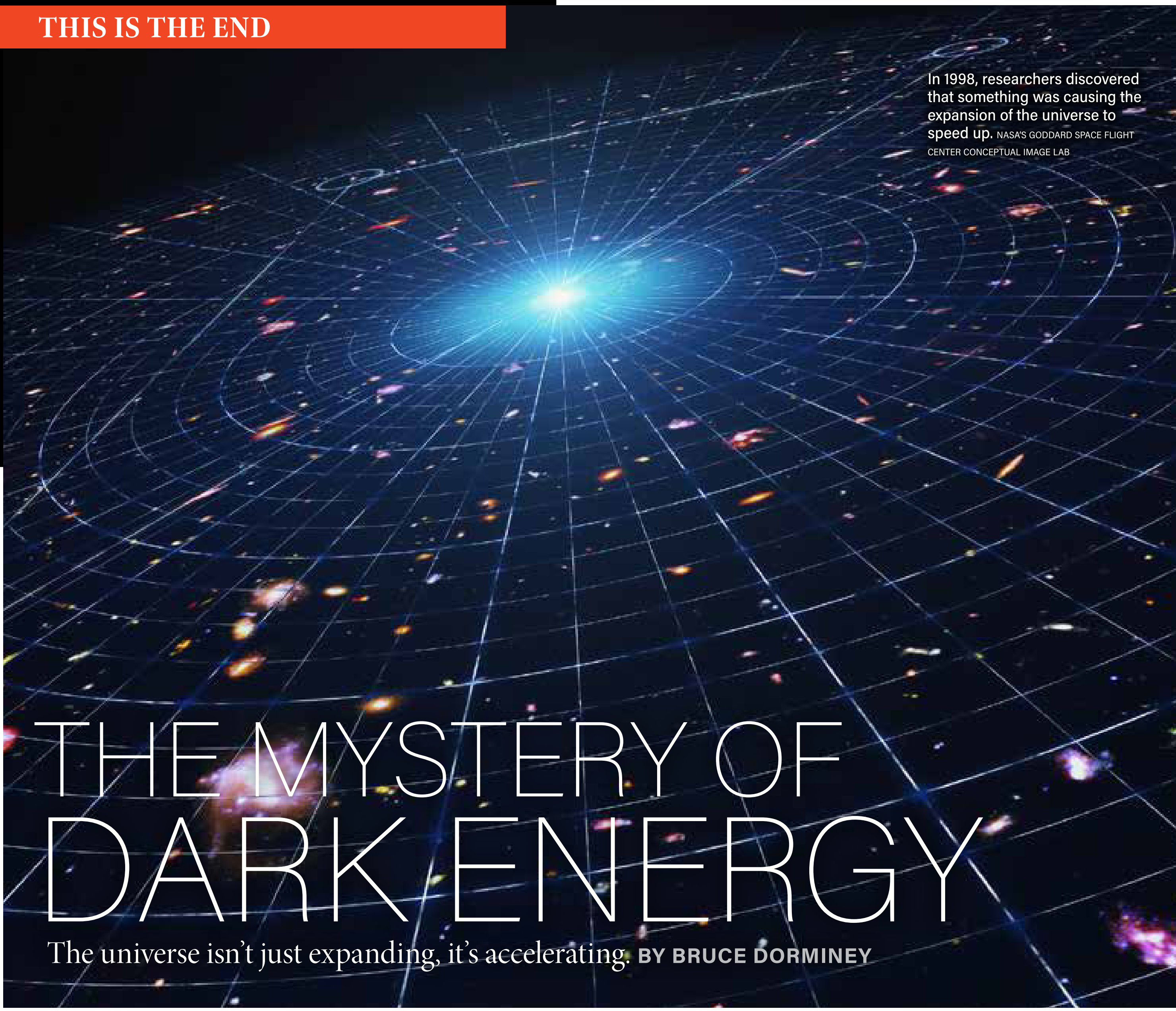
About a googol years from now — that's a 1 followed by 100 zeroes — the last objects in the universe, supermassive black holes, will finish evaporating via Hawking radiation. After this, the universe enters a so-called Dark Era, where matter is just a distant memory.

About a googol years from now, the universe will enter the so-called Dark Era, where matter is just a distant memory.

The second law of thermodynamics suggests that entropy will keep increasing in a system (such as the cosmos) until it hits a maximum level. In real terms, that means that at some point, the universe will ultimately reach a state where all energy — and, hence, heat — is uniformly distributed. The final temperature of the entire universe will hover a smidge above absolute zero.

So, rather than mirroring Revelation, the death of our cosmos will likely resemble the beginning of Genesis: All will be empty and dark.

Eric Betz *is a frequent* Astronomy *contributor. Whatever our cosmos' final fate, he's fairly sure our species won't survive long enough to worry about it.*



In 1998, researchers discovered that something was causing the expansion of the universe to speed up. NASA'S GODDARD SPACE FLIGHT CENTER CONCEPTUAL IMAGE LAB

THE MYSTERY OF DARK ENERGY

The universe isn't just expanding, it's accelerating. BY BRUCE DORMINEY

For almost a century, astronomers have known that the universe is expanding. Space-time is stretching itself out over billions of light-years, carrying the galaxies within it apart, like raisins embedded within a rising loaf of bread. This steady expansion, pitted against the cosmos' urge to collapse under its own gravity, means there are two main scenarios for how the universe will eventually end. These scenarios are dubbed the Big Crunch — where gravity overcomes expansion and the Big Bang occurs in reverse — and the Big Freeze — where gravity loses out to the expansion and all matter is isolated by unfathomable distances. (See "The Big Crunch vs. the Big Freeze," page 50.)

For a while, researchers believed the universe's fate was leaning toward the final scenario. But, in the late 1990s, astronomers discovered something unexpected that changed our understanding of the future of the universe: The most distant galaxies weren't just moving away from us. They were accelerating.

A cosmological puzzle

This phenomenon was independently discovered by two teams of astronomers who were measuring distant supernovae to calculate the precise rate at which the universe was expanding, expecting to find it slowing down. Three of these scientists — Saul Perlmutter, Adam Riess, and Brian Schmidt — shared the 2011 Nobel Prize in Physics for their discovery.

The award-winning observations came from a survey of distant type Ia supernovae. Astronomers believe these

Though astronomers cannot see dark matter directly, they can infer its location from observations. The distribution of dark matter (magenta) in supercluster Abell 901/902 is revealed in this photo by combining a visible light image of the supercluster and a dark matter map of the area. VISIBLE LIGHT: ESO, C. WOLF (OXFORD UNIVERSITY, U.K.), K. MEISENHEIMER (MAX-PLANCK INSTITUTE FOR ASTRONOMY, HEIDELBERG), AND THE COMBO-17 COLLABORATION. DARK MATTER MAP: NASA, ESA, C. HEYMANS (UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER), M. GRAY (UNIVERSITY OF NOTTINGHAM, U.K.), M. BARDEN (INNSBRUCK), AND THE STAGES COLLABORATION

explosions are triggered when a white dwarf — the dense remnant of a Sun-like star — accretes matter that pushes it over a physical mass limit. That limit is the same for all white dwarfs, making all type Ia supernovae the same true brightness. This property made these supernovae ideal standard distance markers, or standard candles, in the mid-1990s.

The two teams were actually looking back into time for the onset of cosmic deceleration: They were looking for the point in time at which gravity gained the upper hand over the cosmos' rapid acceleration after the Big Bang. This moment would mark a turnaround, as gravity finally started to slow the rate at which galaxies and clusters of galaxies are pulled away from one another by the expansion of the universe.

Since scientists know the true brightness of the standard candles, they could anticipate how bright these distant supernovae would be if expansion was slowing down. But instead, they found the observed type Ia supernovae were 25 percent fainter than expected, proving that the universe's expansion isn't slowing down, but instead is speeding up.

By the end of 1998, both teams had submitted papers detailing their findings to academic journals. Perlmutter's team published its paper in *The Astrophysical Journal* and Riess and Schmidt's team published in *The Astronomical Journal.*

The conclusion of both: A large percent of the universe is made up of something previously undiscovered and unexpected. And this so-called dark energy is overpowering gravity and pushing space-time apart from within.

A lot of missing pieces

The composition of the universe is surprisingly tricky to pin down. Besides dark energy, space is also filled with an invisible form of matter known as dark matter. Astronomers

The Hubble Space Telescope examined the most distant type Ia supernovae visible to the spacecraft to measure the expansion rate of the universe. The observations revealed the existence of a mysterious force, known as dark energy, that is causing the universe's expansion to accelerate. NASA, ESA, AND A. RIESS (STSCI)

now know that normal, visible matter makes up just 5 percent of the universe, while enigmatic dark matter and dark energy constitute 26 percent and 69 percent, respectively. In other words, astronomers don't really understand what about 95 percent of the universe is really made of.

And even decades after their discovery, scientists still know shockingly little about the "dark" forces that rule our universe. "Understanding and measuring dark matter and dark energy is hard," says Riess. "Imagine bumping around in a dark room, occasionally touching an elephant, having never seen one, and [trying to understand] what it is, what it looks like."

"If all records are lost, future civilizations might not ever know about other galaxies." For them, he says, "[The universe] will be a cold, dark, lonely place."

But the dark room is the size of the universe and instead of touching the elephant, astronomers can only see the effects it has on other objects. Astronomers can see that dark matter gravitationally interacts with visible matter, so they suspect it to be made up of one or more unknown particles.

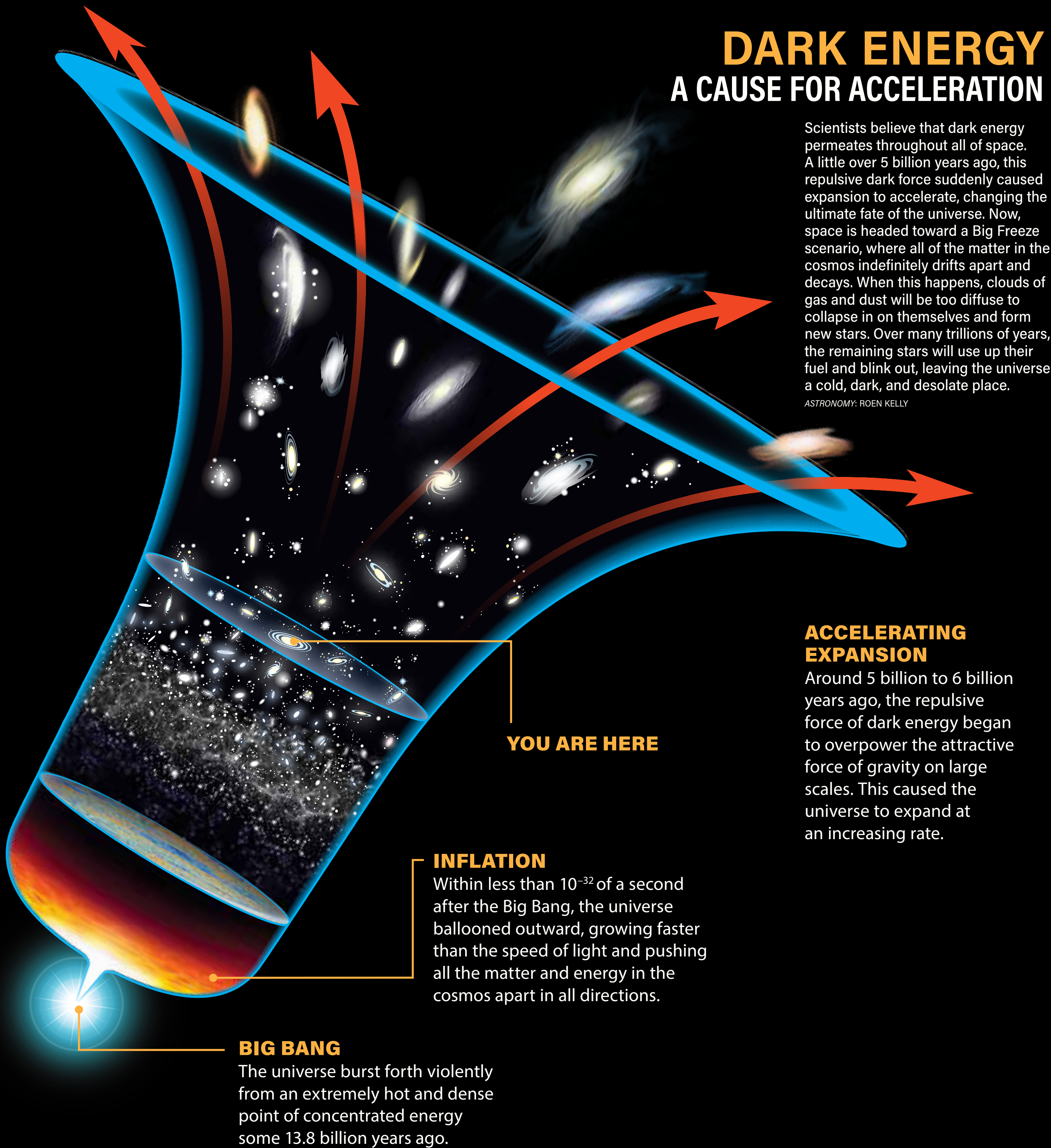
Dark energy could be a fifth fundamental force of the universe. (The known four are: the weak force, the strong force, gravity, and electromagnetism.) But its exact properties are still a mystery, especially since dark energy seems to have randomly turned itself on. Riess says the most recent measurements show that dark energy really kicked off this acceleration about 5 billion to 6 billion years ago, and it's been the dominant force ever since.

The simplest explanation for dark energy is that it is the intrinsic energy of space itself. Albert Einstein initially introduced such a concept to allow for a flat universe when laying out his theory of relativity. Einstein's so-called cosmological constant is a repulsive force that counteracts the attractive force of gravity to allow for a universe that neither collapses nor expands. But, in the end, Einstein dismissed his concept after Edwin Hubble observed the universe expanding. The Nobel-winning supernovae work in the 1990s resurrected the cosmological constant and related it to dark energy.

What lies ahead

To ultimately resolve this dark energy puzzle, Riess says scientists will need more than just measurements. The world's best theoretical physicists have tried to work out a grand unified theory of physics that fully explains all aspects of the universe. But so far, gravity and quantum physics don't seem to mesh, despite the fact that theorists believe their unification is essential to any theory that will also explain dark energy.

One thing scientists have been able to figure out, however,



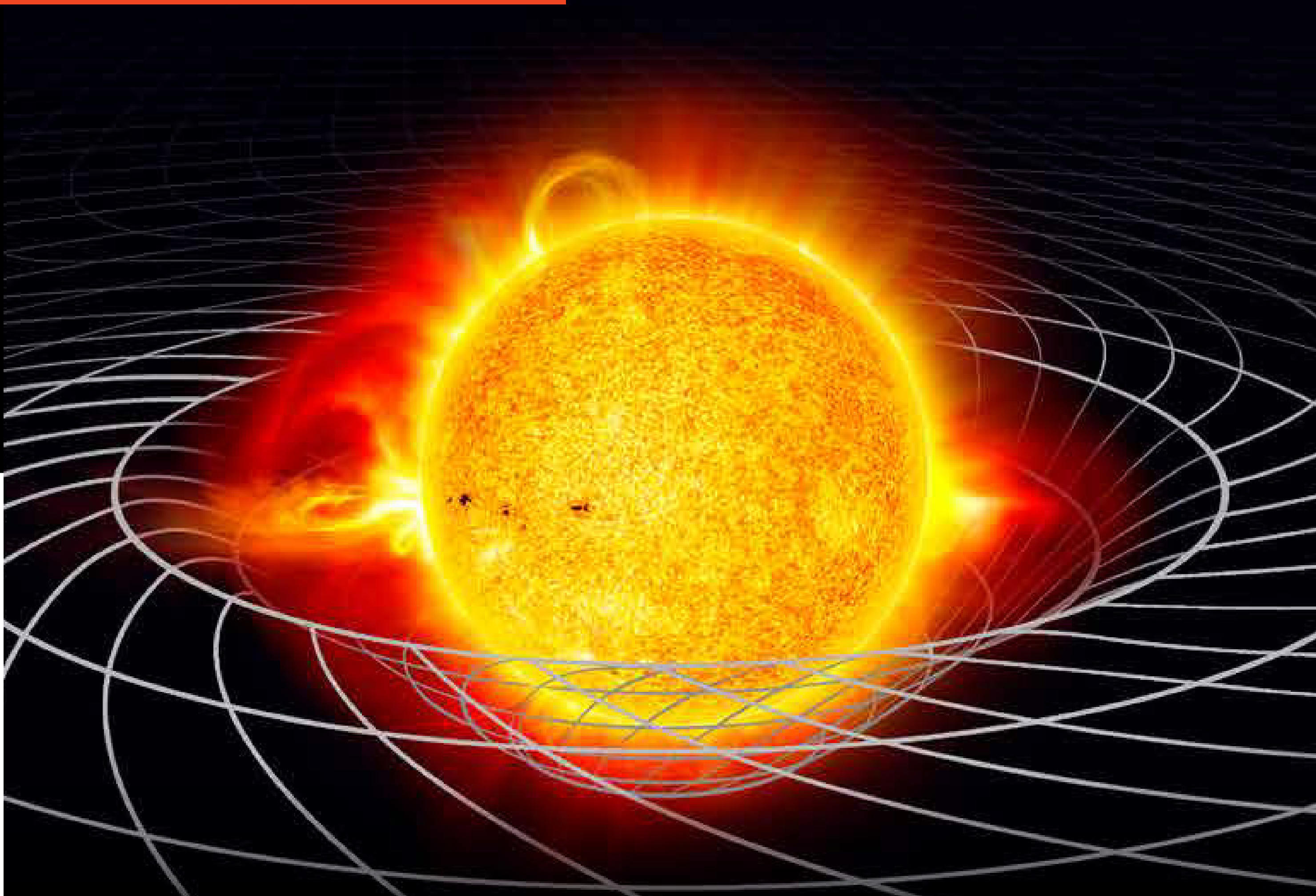
ASTRONOMY: ROEN KELLY

is the profound impact dark energy will have on the universe in the distant future.

If the contribution of dark energy grows as the universe ages, the universe will expand progressively faster over time. Other galaxies beyond our Local Group — which will have merged into a single giant galaxy nicknamed Milkomeda — will eventually be whisked out to such great distances that any far-future occupants of our solar system wouldn't be able to view them.

In fact, Alexei Filippenko, an astronomer at University of California, Berkeley, who has worked with both teams that discovered dark energy, says, "If all records are lost, future civilizations might not ever know about other galaxies." For them, he says, "[The universe] will be a cold, dark, lonely place."

Bruce Dorminey *is a longtime* Astronomy *contributor and author of* Distant Wanderers: The Search for Planets Beyond the Solar System *(Springer Science & Business Media, 2001). He also hosts the weekly podcast* Cosmic Controversy.



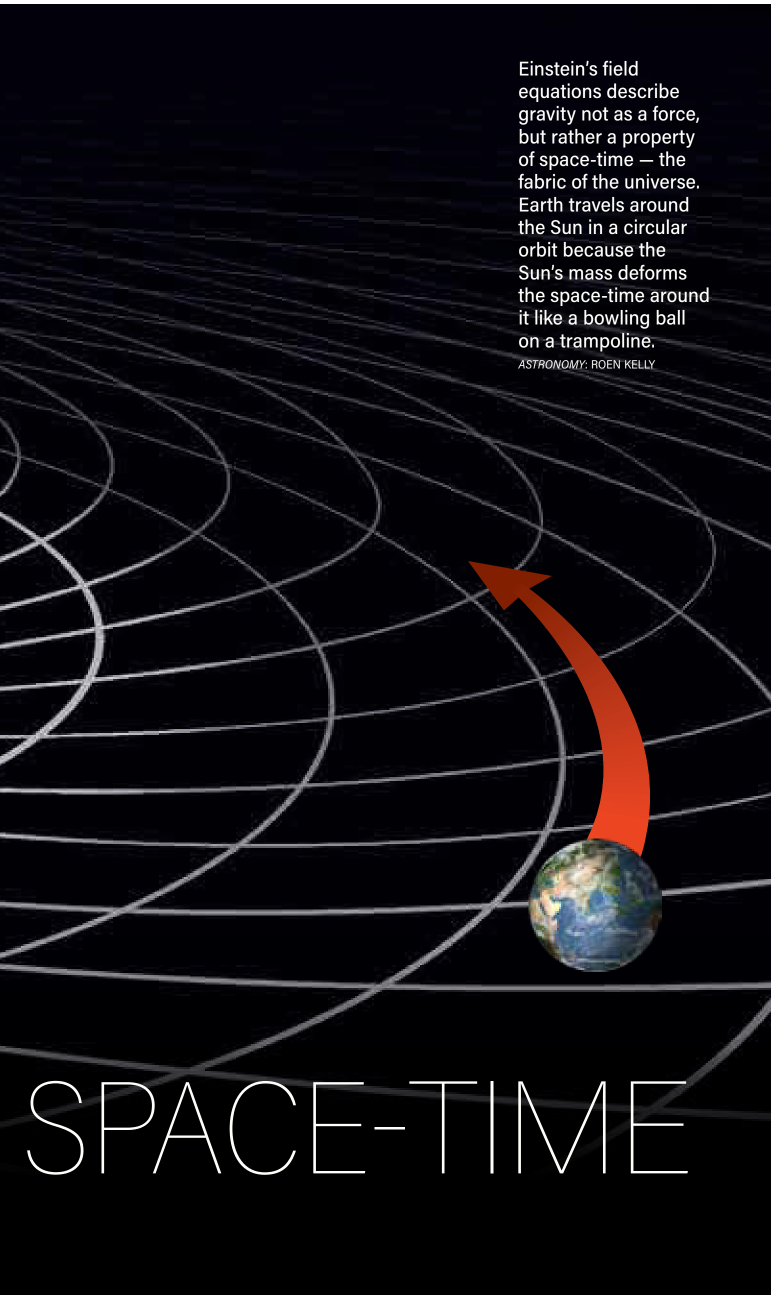
EXPLORING THE SHAPE OF

The afterglow of the Big Bang reveals the geometry of the universe. BY AVI LOEB

In ancient times, scholars such as Aristotle thought that heavy objects would fall faster than lightweight objects under the influence of gravity. About four and a half centuries ago, Galileo Galilei decided to test this assumption experimentally. He dropped objects of different masses from the Tower of Pisa and found that gravity actually causes them all to fall the same way. More than 300 years later, Albert Einstein was struck by Galileo's finding. He realized that if all objects follow the same trajectory under gravity, then gravity might not be a force but rather a property of space-time — the fabric of the universe, which all objects experience in the same way.

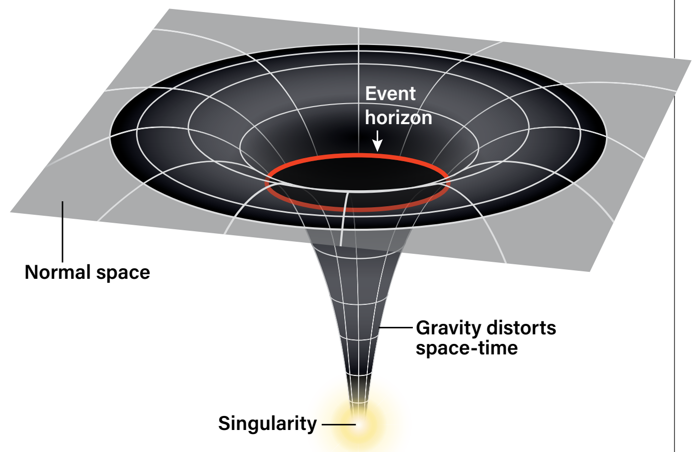
In one of the most important advances in modern physics, Einstein recognized that when space-time is curved, objects do not follow straight lines. He reckoned that Earth, for example, orbits the Sun in a circle because the Sun curves space-time in its vicinity. This is similar to the path of a ball on the surface of a trampoline whose center is weighed down by a person.

In November 1915, Einstein published the mathematical equations that established the foundation for his general theory of relativity. These equations describe the link between matter and the space-time in which it resides, showing that mass deforms space-time and influences the path of matter. In the words of physicist John Wheeler: "Space-time tells matter how to move and matter tells space-time how to curve."



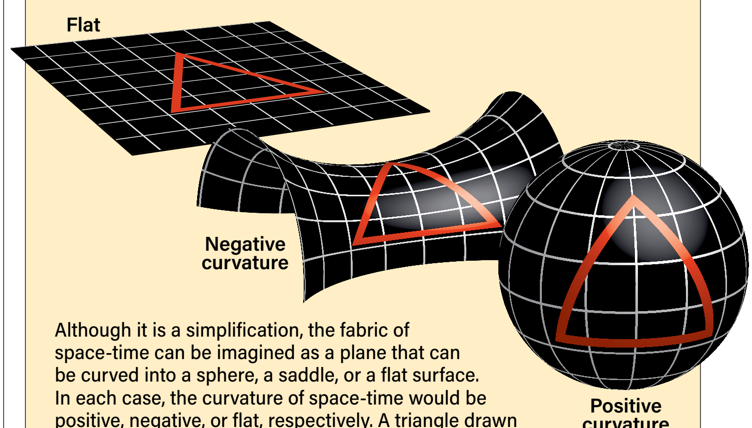
Einstein's field equations describe gravity not as a force, but rather a property of space-time — the fabric of the universe. Earth travels around the Sun in a circular orbit because the Sun's mass deforms the space-time around it like a bowling ball on a trampoline. *ASTRONOMY*: ROEN KELLY

SPACE-TIME AROUND A BLACK HOLE



Schwarzschild's solution to Einstein's equations describes space-time around a spherical mass. Given enough mass packed into a small enough space — a black hole — Einstein's theory breaks down at the central point, called the singularity. Theorists suspect once quantum effects are incorporated, this breakdown will disappear. *ASTRONOMY*: ROEN KELLY

THE SHAPE OF SPACE-TIME



Although it is a simplification, the fabric of space-time can be imagined as a plane that can be curved into a sphere, a saddle, or a flat surface. In each case, the curvature of space-time would be positive, negative, or flat, respectively. A triangle drawn in a universe with positive curvature would have internal angles summing more than 180°; a triangle drawn in a negative universe would enclose less than 180°. In a flat universe, the angles add up to exactly 180°. *ASTRONOMY*: ROEN KELLY

Schwarzschild's solution

A few months later, while serving on the German front during World War I, Karl Schwarzschild became the first to derive a solution to Einstein's equations. His solution describes the curved space-time around a point of mass, labeled by Wheeler half a century later as a "black hole." Schwarzschild's solution showed that the curvature of space-time diverges to infinity at the centermost point. This point is called the singularity because it is the singular point where Einstein's theory breaks down.

The breakdown occurs because Einstein's theory is missing a key component: quantum mechanics. Despite many attempts to unify general relativity with quantum mechanics (such as versions of string theory or loop quantum gravity), we do not have an experimentally verified version of the theory as of yet.

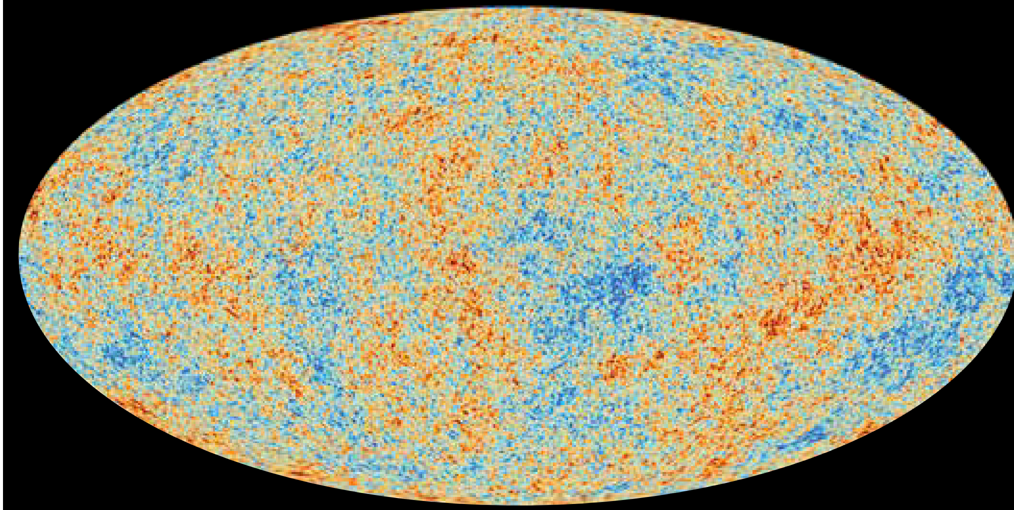
Gladly, the rest of space-time is protected from the uncertain description of the singularity. Schwarzschild's solution provides a spherical event horizon that surrounds the singularity at the so-called Schwarzschild radius. The extent of this radius scales with the mass of the object within. No information can escape from inside this event horizon, which is why we cannot see down to the singularity of a black hole.

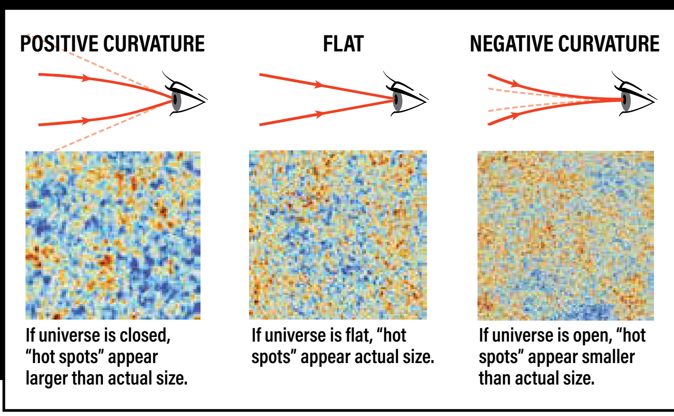
The fabric of the cosmos

But Einstein's equations don't solely apply to the space-time around a black hole. They also describe the evolution of the universe at large.

We know several facts from observing the universe over the past century. First, the universe is expanding. Second, on very large scales, the expanding universe is nearly homogeneous (meaning it has the same density of matter and radiation) and isotropic (meaning it has the same expansion rate in all directions).

A COSMIC TRIANGLE





The characteristic hot and cold spots in the CMB are a few times wider than the diameter of the Full Moon on the sky. By measuring these fluctuations, researchers can form the base of a triangle with Earth at the apex to determine whether the universe is curved (positively or negatively) or flat. This experiment was performed in 2000 and later updated with improved data; the results show a flat universe. *ASTRONOMY*: ROEN KELLY; ESA AND THE PLANCK COLLABORATION

Under these circumstances, Alexander Friedmann, Georges Lemaître, Howard Robertson, and Arthur Walker derived a spherically symmetric solution to Einstein’s equations that describes our universe and its space-time. The curvature of space-time in this solution can be positive (like the surface of a ball), negative (the surface of a saddle) or zero (a flat surface).

In the spirit of Galileo, can we measure the actual cosmic geometry experimentally? The simplest experimental approach is to draw a large triangle through the universe and measure the sum of its angles. For a negative or positive curvature, the sum would be smaller or larger than 180°, respectively, whereas for a flat geometry it would be exactly 180°.

The cosmos has been kind enough to embed the base of this triangle in the cosmic microwave background (CMB). Early on, the universe was hot and dense. The cosmic soup of particles cooled to a temperature below 4,000 Kelvin (about 6,700 degrees Fahrenheit or 3,700 degrees Celsius) 380,000 years after the Big Bang, at which point electrons and protons “recombined” to make hydrogen atoms and the universe became transparent to the CMB, allowing its light to travel unhindered. Therefore, observations of the CMB allow us to witness the universe at the moment of recombination.

The CMB’s brightness is not perfectly uniform across the sky — it varies by roughly one part in 100,000 on a wide range of angular scales. But there is one special scale at the epoch of recombination which cosmologists can calculate: the distance that sound (acoustic) waves traversed over the course of these first 380,000 years of the universe. This acoustic scale can serve as the known base of our triangle. It signifies the spatial separation of parcels of the cosmic gas that could have been in acoustic contact with each other. By measuring this special correlation scale for CMB brightness fluctuations on the sky, we can draw an isosceles triangle with Earth at the apex. Knowing the height and base length of the triangle, as well as measuring the angle spanned by the acoustic scale on the sky, would tell us whether the sum of the angles in this triangle equals or deviates from 180° — and hence the curvature of the universe.

The geometry of the universe is the simplest one we can imagine: flat!

Our flat universe

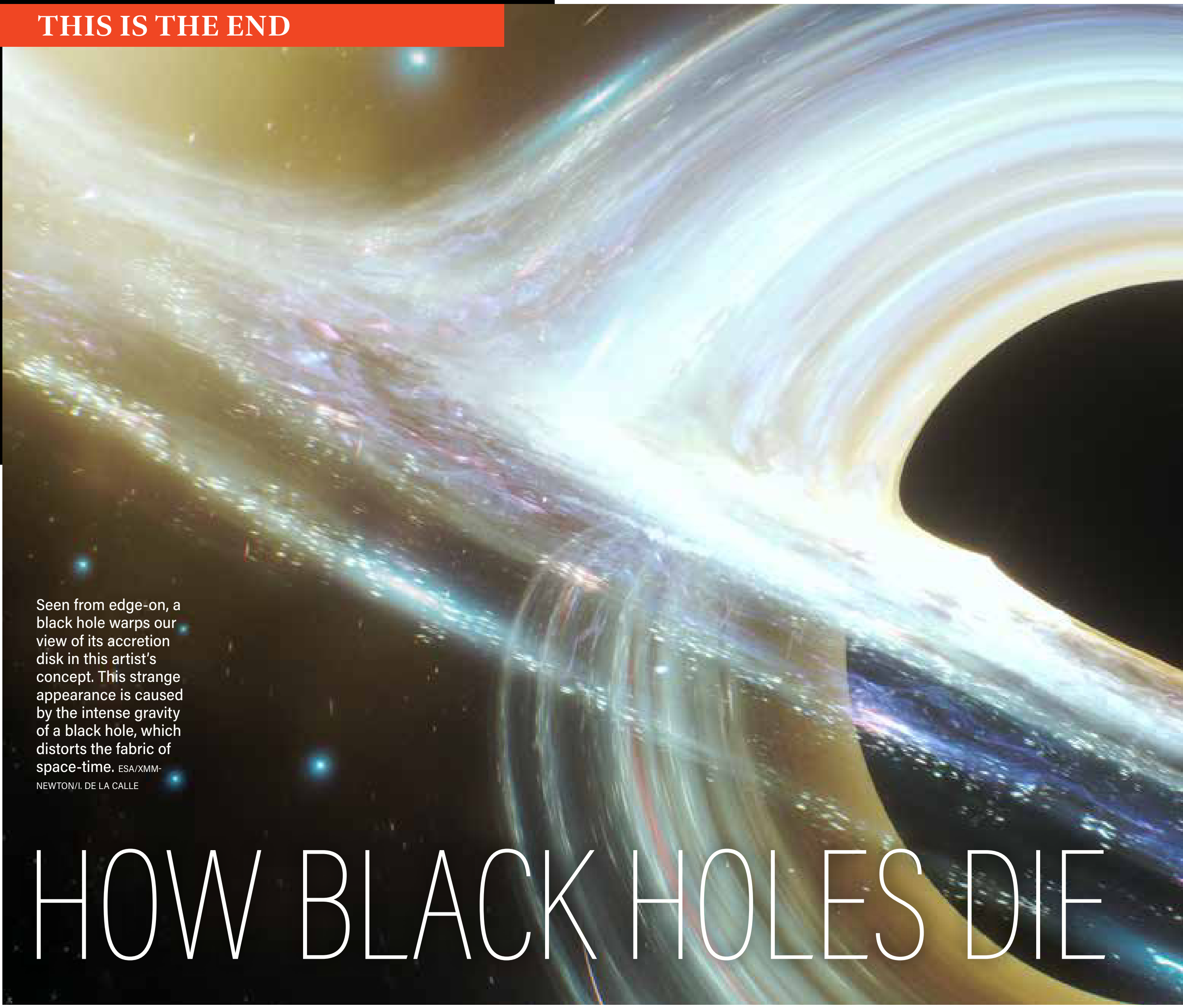
Researchers performed this experiment in 2000 and later refined the measurement to a high level of precision with the latest data from the Planck satellite. The result revealed that the geometry of the universe is the simplest one we can imagine: flat!

Why is the universe so simple? Obviously, nature is under no obligation to represent the simplest solution to Einstein’s equations.

The theory of cosmic inflation provides one possible explanation. If the universe went through an early period during which it inflated exponentially, then all traces of its initial curvature would be flattened out. Inflation serves as the cosmic iron, erasing all pre-existing wrinkles from space-time. Quantum fluctuations of the vacuum during inflation might have led to the slight brightness fluctuations of the CMB that later seeded the formation of galaxies like the Milky Way. If our cosmic roots were formed then, we owe our existence to the quantum realm.

Interestingly, our expanding universe is now entering a new phase of exponential expansion, due to dark energy. Here again, we have no idea how long this inflationary phase will last. If it continues for more than 10 times the current age of the universe, our galaxy will be left alone, surrounded by darkness with no other source of light in sight. It would be the most dramatic incarnation of social distancing from extragalactic civilizations that we can imagine following the era of COVID-19.

Avi Loeb *chairs the Board on Physics and Astronomy of the National Academies and serves as the founding director of Harvard’s Black Hole Initiative, and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. His new book,* Extraterrestrial *(Houghton Mifflin Harcourt), will be out January 2021.*



Seen from edge-on, a black hole warps our view of its accretion disk in this artist's concept. This strange appearance is caused by the intense gravity of a black hole, which distorts the fabric of space-time. ESA/XMM-NEWTON/I. DE LA CALLE

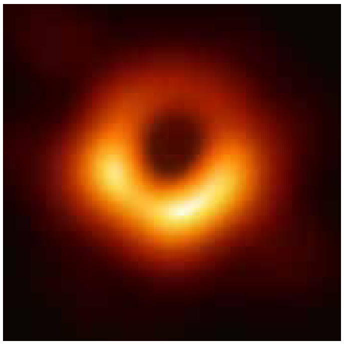
HOW BLACK HOLES DIE

Long after the last stars fade, black holes will herald the end of the universe with a spectacular show of fireworks. BY NOLA TAYLOR REDD

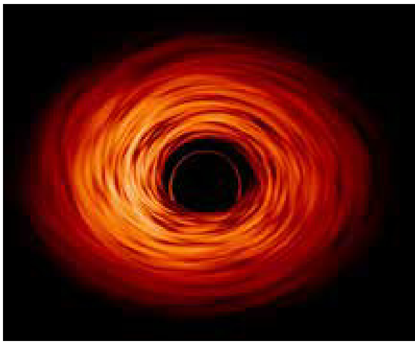
Black holes are regions of space-time where gravity rules: The gravitational pull of a black hole is so strong that nothing, not even light, can escape. They range in size from stellar-mass black holes, whose masses can run from five to 100 times that of the Sun, all the way to supermassive black holes, which can reach well over a billion solar masses. Astronomers now believe supermassive black holes hide within the heart of most galaxies. (A notable exception to this rule is M33, which, despite being the third largest member of our Local Group, appears to lack a central supermassive black hole.)

Right now, the universe is in its Stelliferous Era, when stars and galaxies are continuously being born. Eventually, the ingredients to make these objects will be used up, and the stars in the night sky slowly will wink out, leaving black holes as the universe's only occupants.

But even the black holes will one day die. And when they do, these monsters won't go gently into the night. A burst of fireworks will light up the universe in the final moments

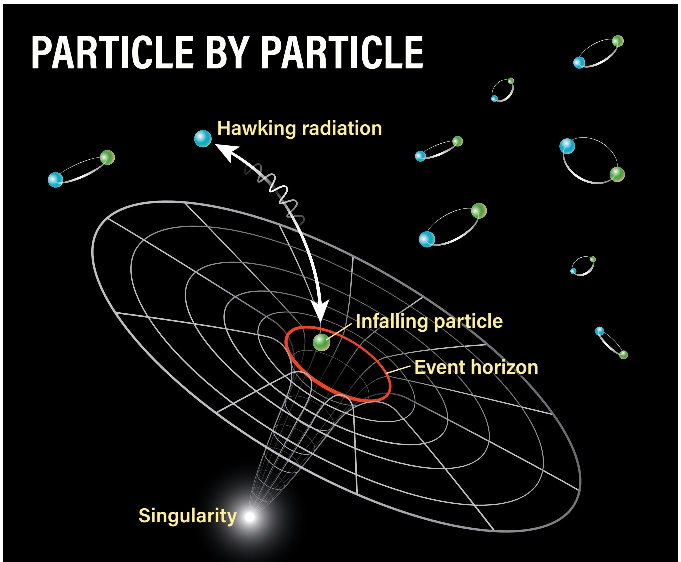


Using the Event Horizon Telescope, scientists accomplished the impossible, capturing an image of a black hole. This historic image shows the shadow of the supermassive black hole at the heart of the Messier 87 galaxy. EHT COLLABORATION



Accretion disks around black holes act like bull's-eyes for scientists. The gas in the disk heats up as the material piles up around the event horizon, revealing the shadow of a black hole. NASA'S GODDARD SPACE FLIGHT CENTER/JEREMY SCHNITTMAN

PARTICLE BY PARTICLE



Latent energy (quantum fluctuations) in the fabric of space-time may cause pairs of virtual particles to pop into existence throughout the universe. If such a pair is created right on the event horizon, or the boundary, of a black hole, one particle may fall in while the other barely escapes, taking with it a minuscule amount of energy and therefore mass from the black hole. This theoretical phenomenon is known as Hawking radiation. *ASTRONOMY*: RICK JOHNSON

of each black hole, heralding the end of the era.

Cheating death

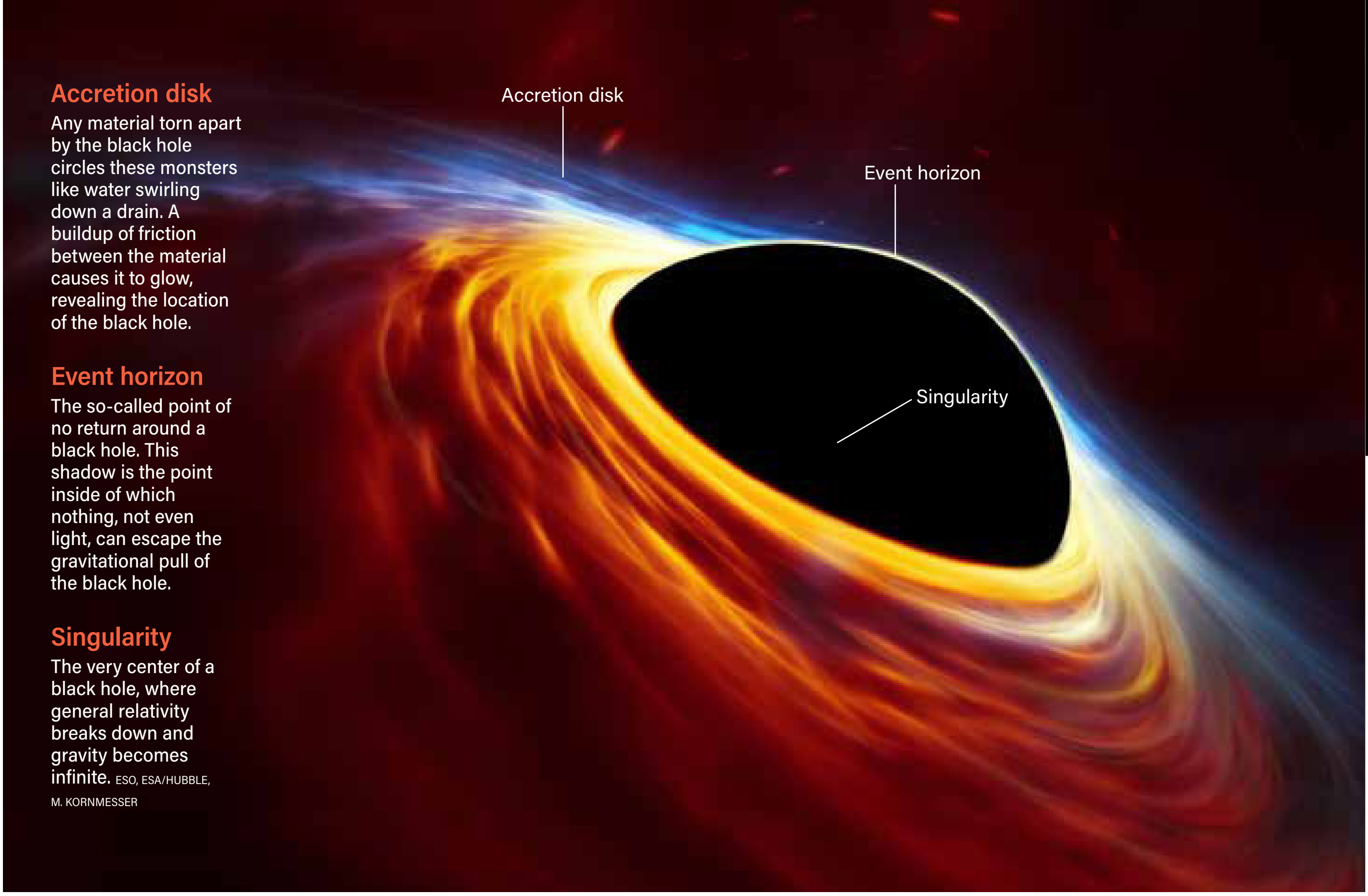
Black holes survive by gobbling down the gas and stars around them, and it's their gluttony that gives them away. They are often surrounded by accretion disks of material they've torn apart and sucked close, like water swirling down a drain. As material draws closer, it begins to travel faster and faster, piling up around the black hole. Friction among the dust generates heat, causing the accretion disk to glow, which outlines the shadow of the black hole — or its event horizon. "It wants to hide but it does a pretty bad job of it sometimes," says Sheperd Doeleman, a black hole researcher at Harvard University and director of the Event Horizon Telescope, which snapped the first photo of a black hole in 2019.

Besides giving a black hole away, the event horizon is also the key to a black hole's death.

The material that crosses a black hole's horizon is lost forever, as nothing can escape the grip of these gluttonous monsters. At least, that's what our current understanding of gravity dictates. But this so-called point of no return fails to take quantum mechanics into account. (Physicists are still working to develop a unified theory of quantum gravity.) In 1974, Stephen Hawking proved that, from a quantum perspective, escape from a black hole is possible, though it is very slow.

While empty space may seem devoid of energy, it isn't — according to quantum mechanics, the energy of a vacuum fluctuates slightly over time. Those fluctuations manifest as pairs of particles — a particle and an antiparticle — that pop into and out of existence throughout the universe. Because energy cannot be created from nothing, one of the particles will have positive energy and the other negative. These particle pairs usually immediately annihilate one another. But if the particles appear at the boundary of a black hole's event horizon, it's possible for the particle with negative energy to fall into the black hole, while the particle with positive energy

THE ANATOMY OF A BLACK HOLE



Accretion disk
Any material torn apart by the black hole circles these monsters like water swirling down a drain. A buildup of friction between the material causes it to glow, revealing the location of the black hole.

Event horizon
The so-called point of no return around a black hole. This shadow is the point inside of which nothing, not even light, can escape the gravitational pull of the black hole.

Singularity
The very center of a black hole, where general relativity breaks down and gravity becomes infinite. ESO, ESA/HUBBLE, M. KORNMESSER

escapes. It then appears that the black hole has radiated a particle away. Einstein showed that energy and mass are proportional with his equation $E = mc^2$. Therefore, the negative energy from the forsaken particle actually removes mass from the black hole, causing it to shrink.

But don't expect a black hole to disappear any time soon. It takes a shockingly long time for a black hole to shed all of its mass as energy via Hawking radiation. It would take 10^{100} years, or a googol, for a supermassive black hole to fully disappear. "The entire age of the universe [is] a fraction of [the time] it would take," says Priyamvada Natarajan, a researcher at Yale University who probes the nature of black holes. "As far as we're concerned, it is eternity."

Death throes

Exactly how long an individual black hole lives depends strongly on its mass. The larger a black hole gets, the longer it takes to evaporate. "In that sense, [a black hole] can cheat death by growing," Doeleman says.

He compares the process to an hourglass, where the sand at the top is the amount of time a black hole has left. By gobbling down more stars and gas, a black hole continues to add sand to the hourglass of its life, even as individual particles trickle out. "As long as there is material around [to eat], the black hole can keep resetting its clock," Doeleman says. Eventually, as the universe ages, the material around a black hole will run out and its doomsday clock will start ticking.

"It's almost like a million nuclear fusion bombs going off in a very tiny region of space."

As a black hole evaporates, it slowly shrinks and, as it loses mass, the rate of particles escaping also increases until all the remaining energy escapes at once. In the final tenth of a second of a black hole's life, "you will have a huge flash of light and energy," Natarajan says. "It's almost like a million nuclear fusion bombs going off in a very tiny region of space."

By Earth's standards, that's a lot, significantly more than the total nuclear arsenal of all nations. In astronomical terms, not so much. The most powerful supernova yet recorded (ASSASN-15lh) was 22 trillion times more explosive than a black hole will be in its final moments.

It doesn't matter how small or how massive a black hole is, their closing fireworks are exactly the same. The only difference is how long it will take a black hole to explode. But once a black hole gobbles down its last meal, all that's left is for the sand grains to relentlessly tumble down until there's nothing left.

Nola Taylor Redd *is a freelance science journalist with a focus on space and astronomy. In addition to* Astronomy, *she has written for publications including* Scientific American, *the BBC, and* Smithsonian. *She lives in Atlanta.*

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MARKETPLACE

A COLD, LONELY DEATH

Everything — from creatures to stars to black holes — will eventually decay into nothingness. BY DOUG ADLER

ABOVE: As the cosmos ages over an unbelievably long timescale, the stars will fade before matter itself decays. JONATHAN SAUTTER

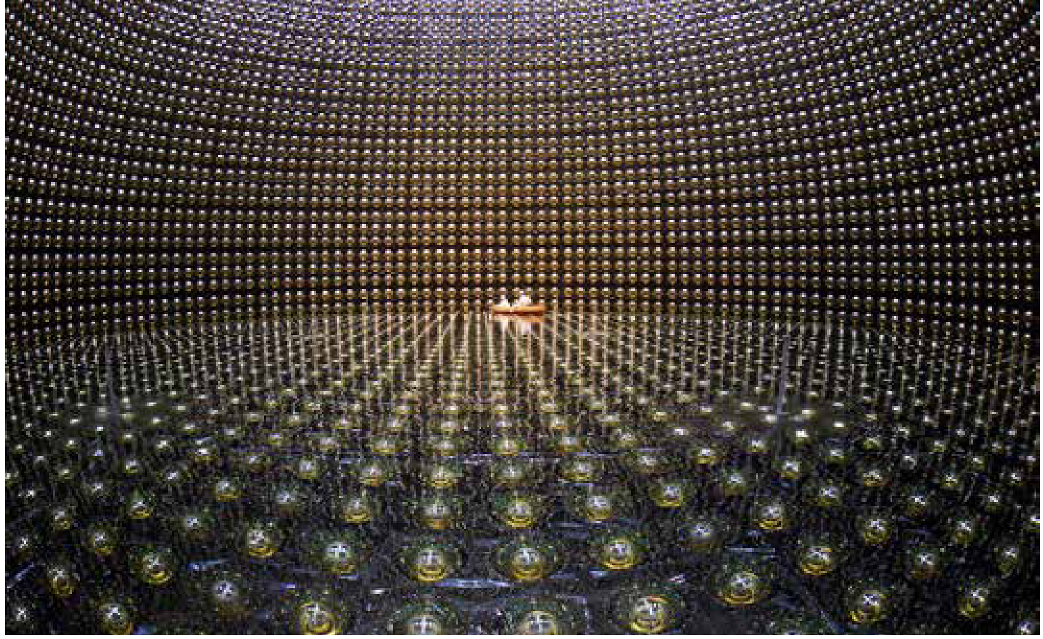
The universe, like everything else, was born, matures, and will eventually die. But exactly how and when that death will occur remains one of the greatest mysteries in the field of cosmology.

Many scientists have previously categorized cosmic time into different eras. Fred Adams and Greg Laughlin, for example, wrote a popular science book called *The Five Ages of the Universe* (Free Press, 2000). According to the pair, the first era was the **Primordial Era**, during which the Big Bang occurred, kicking off the cosmos' ongoing expansion.

The next era, which we're currently in, is known as the **Stelliferous Era**, in which matter is organized into stars, planets, nebulae, and larger constructs, such as galaxies and galaxy clusters. This era is hypothesized to run from about 10^6 to 10^{14} (1 million to 100 trillion) years after the Big Bang. Once all stars exhaust their hydrogen fuel and go dark, we will have entered the **Degenerate Era**. This period is hypothesized to take place between 10^{15} and 10^{39} (1 quadrillion to 1 duodecillion) years after the Big Bang. It will be dominated by stellar remnants such as black holes, white dwarfs, brown dwarfs, and neutron stars. As time unceasingly marches on, the universe will continue to cool and darken; eventually, life and matter as we understand it will likely come to an end.

The universe fades to black (holes)

But what happens after that? White dwarfs, brown dwarfs, and neutron stars are expected to eventually die through a process known as proton decay, when the subatomic particles



KAMIOKA OBSERVATORY, ICRR (INSTITUTE FOR COSMIC RAY RESEARCH), THE UNIVERSITY OF TOKYO

Kamioka Observatory, seen here, is located some 3,300 feet (1,000 m) below ground in a mine outside of Kamioka, Japan. The Super-Kamiokande experiment uses a tank filled with about 50,000 tons of pure water surrounded by detectors to seek flashes of Cherenkov light produced by incoming neutrinos — or perhaps, by proton decay.

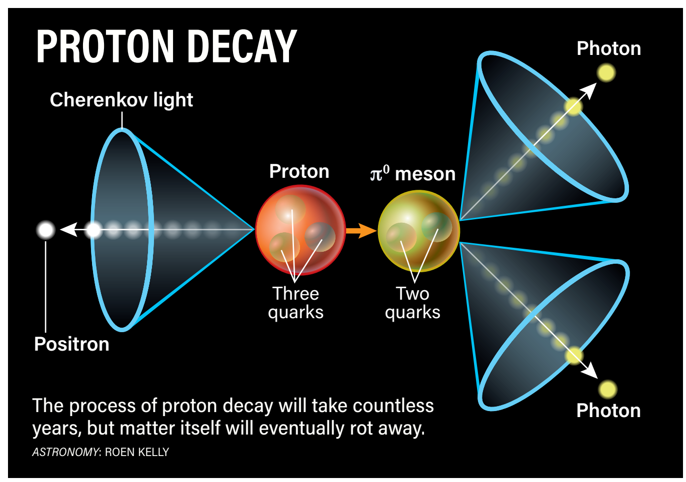
they are made of literally fall apart. Cosmologists predict this will occur late in the Degenerate Era, as the half-life (the time it takes for half of a substance to decay) of a proton is thought to be about 10^{34} years. And when the last remnants of stars rot away at the particle scale, only black holes will remain, dominating what is left of the universe.

The **Black Hole Era**, which is predicted to last from about 10^{40} to 10^{100} (10 duodecillion to 1 googol) years after the Big Bang, spans an unimaginably long stretch of time, even for astronomical timescales. Imagine a universe with no bright stars, no planets, and no life whatsoever — that's the Black Hole Era. Very little heat and light will linger in the universe at this point.

Black holes are so dense and massive that they produce tremendous distortions in the fabric of space-time, forever capturing anything that gets too close. And during the Black Hole Era, these dark beasts' gravitational influence will only increase as they gobble up lingering remnants of ordinary matter.

Still, even these monsters will not last forever. (See "How black holes die," page 60.) Although the popular conception is that "nothing can escape a black hole, not even light," scientists aren't entirely sure that's true. Astronomers believe black holes do emit radiation — in particular, Hawking radiation, named after famed physicist Stephen Hawking, who first proposed the idea. Although Hawking radiation has yet to be detected, if black holes do leak the radiation, it would provide a mechanism by which they could die off — literally evaporating into the cosmos.

However, even for tiny black holes, this process would still take an absurd amount of time. For a stellar-mass black hole, it could take up to 10^{64} years, and for the largest supermassive black holes, it might take as long as a couple googol years — again, that's a 1 followed by 100 zeros — or possibly even longer. Astronomers simply don't have the observational evidence to know for sure.



The process of proton decay will take countless years, but matter itself will eventually rot away.

ASTRONOMY: ROEN KELLY

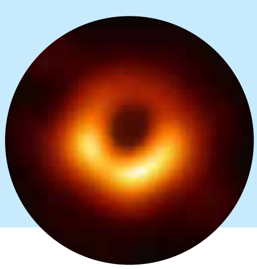
Everlasting darkness

After the last black hole has faded away, it's hard to even comprehend what the universe will be like. The concepts of space and time barely have any real meaning once the last structures have disappeared. The period following the demise of black holes is known as the **Dark Era**, which is expected to begin sometime around 10^{101} years after the Big Bang, though its start depends on how long black holes last. So when — and if — this era ends is anybody's guess.

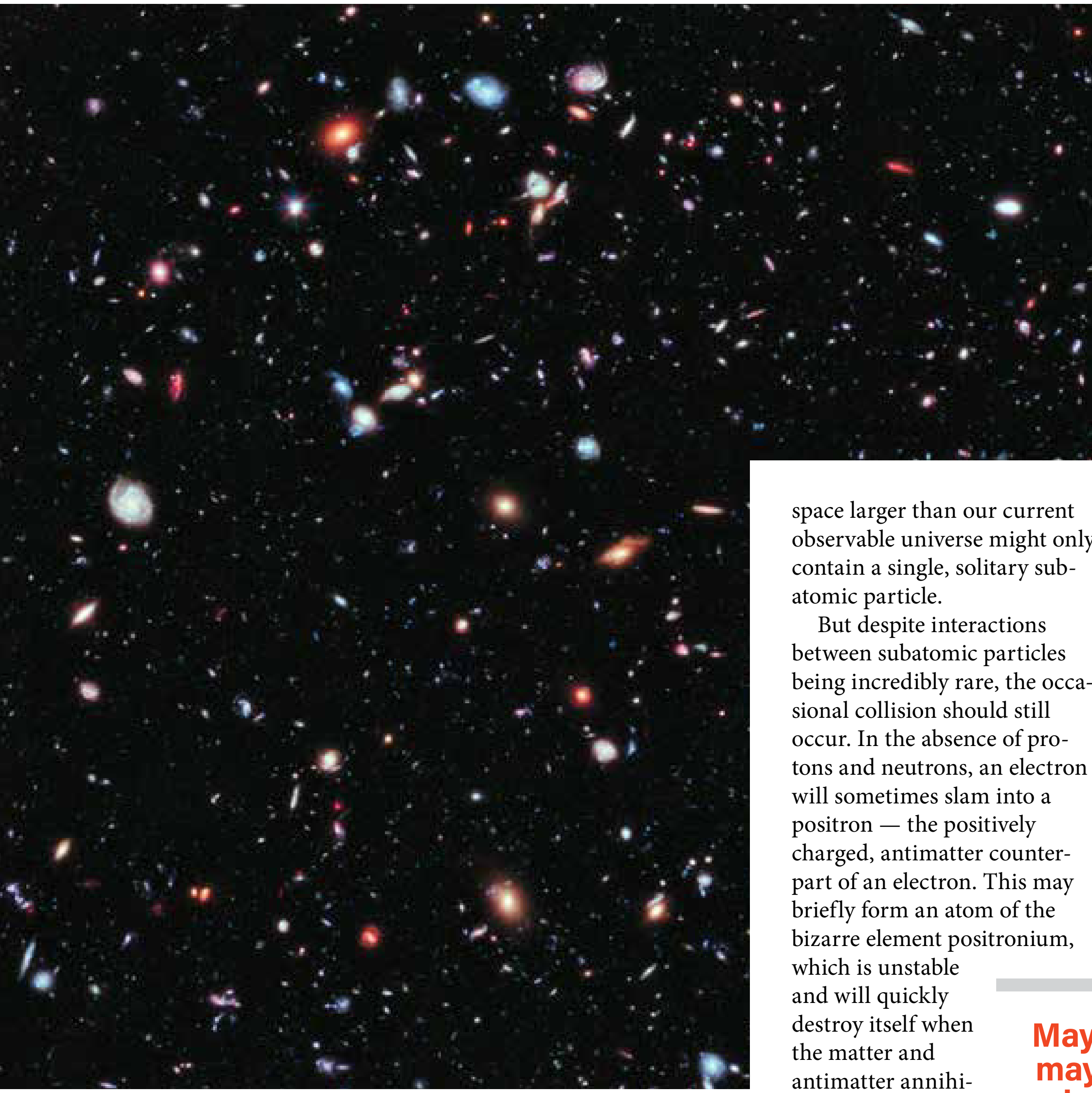
During the Dark Era, the universe will consist of only a few subatomic particles and potentially dark matter, which is an little understood substance that does not absorb, emit, or reflect electromagnetic radiation and may not decay at all. Whatever remains, however, will be very spread out. That's because as the universe cools, it will likely continue to expand. Scientists still debate how much the universe can balloon up, but by the time of the Dark Era, even a volume of

BLACK HOLE FLAVORS

Black holes come in a variety of sizes. The LIGO/Virgo gravitational-wave detectors, for example, have already picked up many mergers between **stellar-mass black holes**, which form when massive stars collapse. But in September 2019, the collaboration announced the first direct detection of gravitational waves from a black hole merger that created a never-before-confirmed **intermediate-mass black hole**, weighing in at about 142 solar masses. Meanwhile, our galaxy's **supermassive black hole**, Sagittarius A*, tips the scales at about 4 million solar masses; H1821+643, in the constellation Draco, is a giant supermassive black hole that weighs in at an astounding 30 billion solar masses. *—Jake Parks*



This first image of the shadow of a black hole was released by the Event Horizon Telescope in April 2019. The bright ring is from the black hole's accretion disk heating matter, which radiates light. In the distant future, black holes will run out of fuel and fade away. EVENT HORIZON COLLABORATION



The famed Hubble Ultra Deep Field, part of which is seen here, reveals how even a relatively empty patch of sky is still filled with countless galaxies. But in the distant future, space will expand and matter will decay to the point where a region of space the size of the current observable universe will only contain a few subatomic particles, if that. NASA/ESA

Our understanding of the cosmos is far from complete. There's a chance our best educated guesses about how the universe will end are missing something major — something that will allow life to survive and thrive forever. NASA

space larger than our current observable universe might only contain a single, solitary subatomic particle.

But despite interactions between subatomic particles being incredibly rare, the occasional collision should still occur. In the absence of protons and neutrons, an electron will sometimes slam into a positron — the positively charged, antimatter counterpart of an electron. This may briefly form an atom of the bizarre element positronium, which is unstable and will quickly destroy itself when the matter and antimatter annihilate each other.

Many cosmologists think the universe will continue to cool, eventually playing out the so-called Big Freeze, when there is no heat remaining anywhere. (See "The Big Crunch vs. the Big Freeze," page 50.) The cosmos will eventually reach a point of total disorder, or maximum entropy. The Second Law of Thermodynamics, which states that the entropy of a closed system (like the entire universe) can only increase, will have finally reached its logical conclusion.

Maybe, just maybe, the universe will end with neither a death nor a rebirth.

Is this cosmic fate guaranteed?

No. Much of the above is theoretical or based on ideas that are difficult or impossible to empirically test.

For example, the Big Crunch offers an alternate vision for how the universe ends — not by simply cooling and expanding to nothingness, but rather by halting its current expansion and bringing everything crashing back in on itself. Essentially, the death of the universe in this scenario would play out like the Big Bang in reverse.

Such a catastrophic collapse would kill any lingering life in the universe — though it's tough to imagine life surviving to this point anyway. Perhaps the Big Crunch would even be followed by another Big Bang, birthing a fresh universe from the ashes of our own.

However, most scientists think the Big Crunch is an unlikely fate. Instead of being guided by gravity, the universe appears to be under the influence of dark energy (see "The mystery of dark energy," page 53), causing space itself to expand at an accelerating rate and making the Big Freeze a more likely end.

These are difficult — and even upsetting — scenarios to ponder. But keep in mind, history has taught us that these theories may someday be superseded by others, markedly changing our predictions about the distant future. Perhaps our cosmological conjectures are still missing a major consideration or two.

Maybe, just maybe, the universe will end with neither death nor rebirth. Indeed, there could be a plot our imaginations have yet to envision, one where the physical laws of the universe allow matter, and life, to press on indefinitely.

Doug Adler *is a frequent* Astronomy *contributor and co-author of* From the Earth to the Moon: The Miniseries Companion *(2020).*